Advances in the Prediction of Shear Events Induced From Mechanical Stimulation

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Contents

- EGS site Soultz-sous-Forêts
- FE Kernel / HEX-S Reservoir Model
- Interpretation GPK3 /
  Stimulation Forecast of GPK4
- Stimulation Planning at Coso EGS Project

INTRODUCING GEOWATT AG

Geothermal Energy utilization

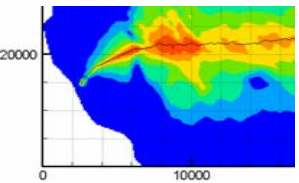
- Resource Evaluation
- Generic studies High- and Low-Enthalpy Systems
- Courses at University and Engineering Schools

Engineering

- Dimensioning Heating/Cooling (BHE-Felder)
- Reservoir Engineering
- Measurements

Hydrogeology

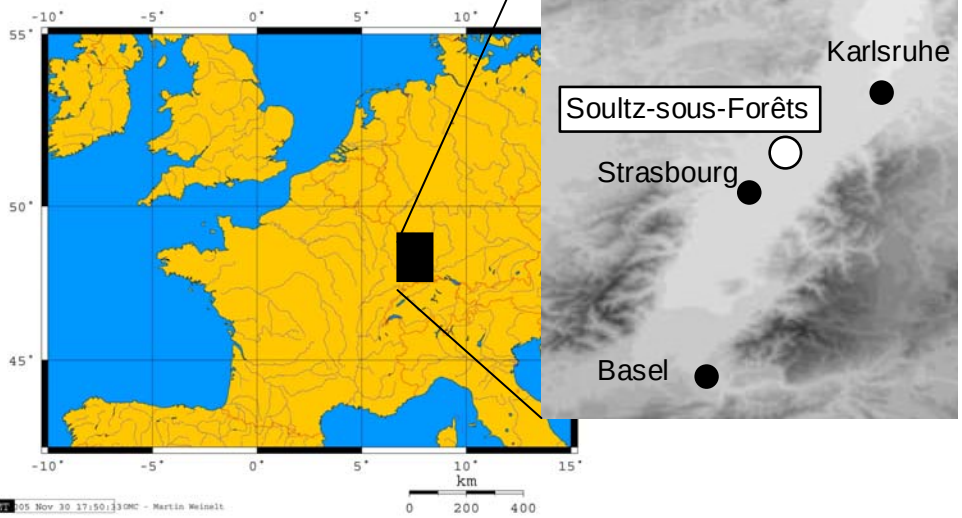
- Tunneling: Inflow scenario
- Flow system

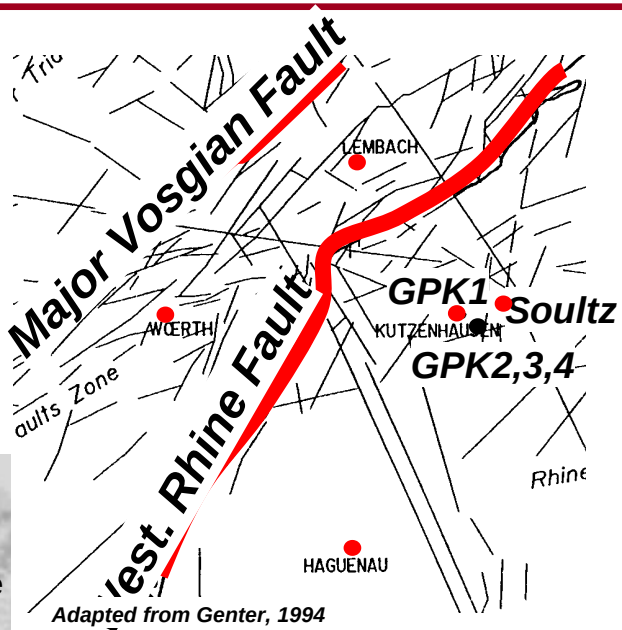


Numerics

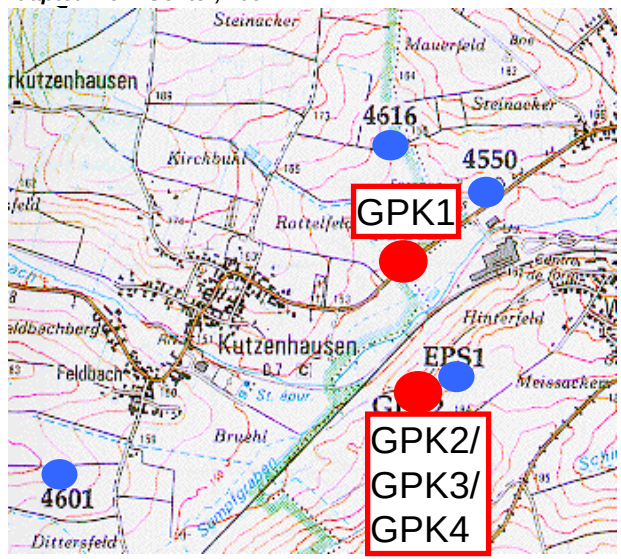
- Coupled 3D-FE calculations
- Data bank
- Specific simulation tools

European EGS Project Soultz s.F.
Location and tectonic setting

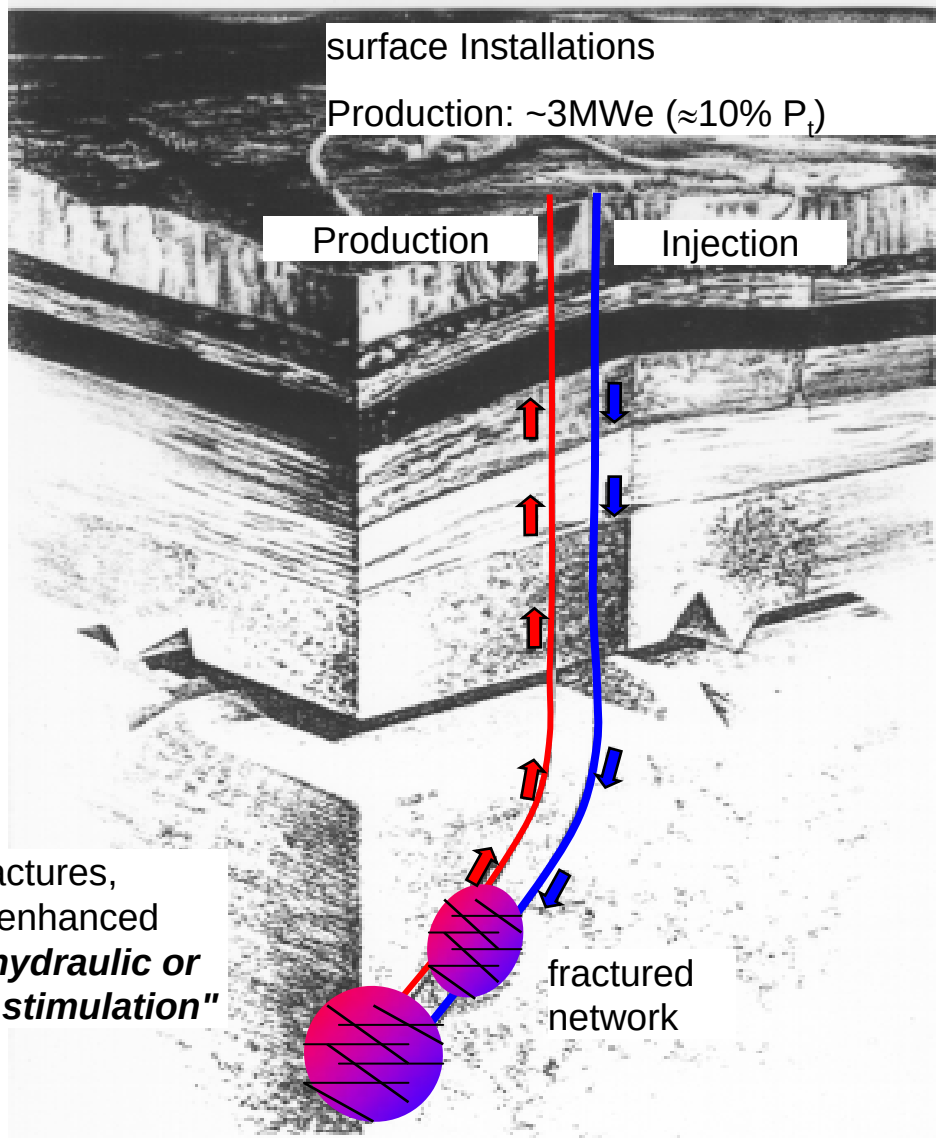




Adapted from Genter, 1994



EGS Concept
(Enhanced Geothermal System)



Natural fractures, artificially enhanced through ***"hydraulic or chemical stimulation"***

EGS - Modeling Approaches

- Essentially fractured medium, Darcy flow; non-Darcy flow at high fluid velocities in fractures
- Hydraulic coupling: advection
- Thermal coupling: buoyancy, density, viscosity
- Mechanical processes play an important role in reservoir development and assessment
  - Fracture mechanics
    - Shear fracturing

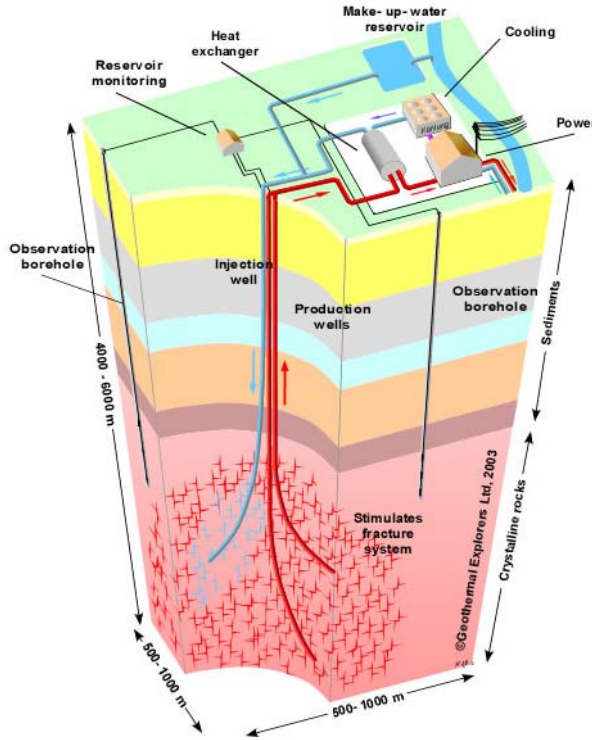
      $$\tau = c + \tan(\Phi) \cdot \sigma_n$$

    - Tensile fracturing

      $$P_f > S + \sigma_{\min}$$

      $$P_f > S + \sigma_{\min} + \alpha \cdot P_p$$

  - Matrix elasticity
    - Poroelasticity
    - Thermoelasiticity
- Injected fluid and formation fluids are different; biphasic flow or multicomponent transport
- Geochemistry also play an important role in reservoir characteristics

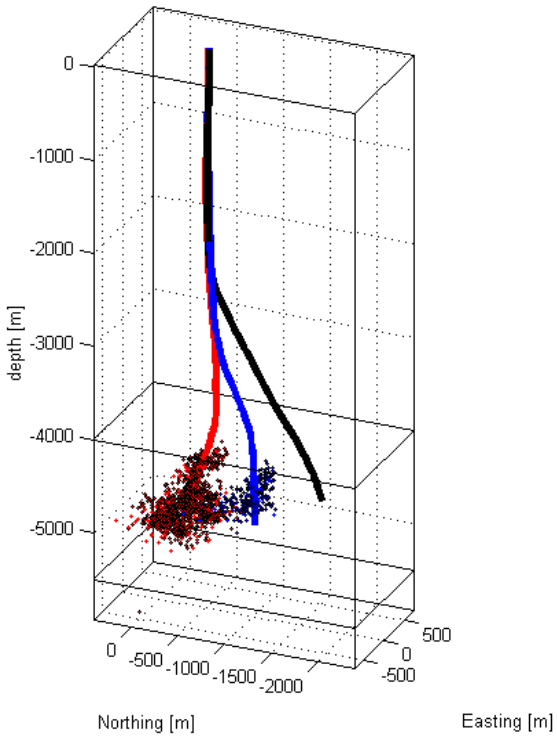


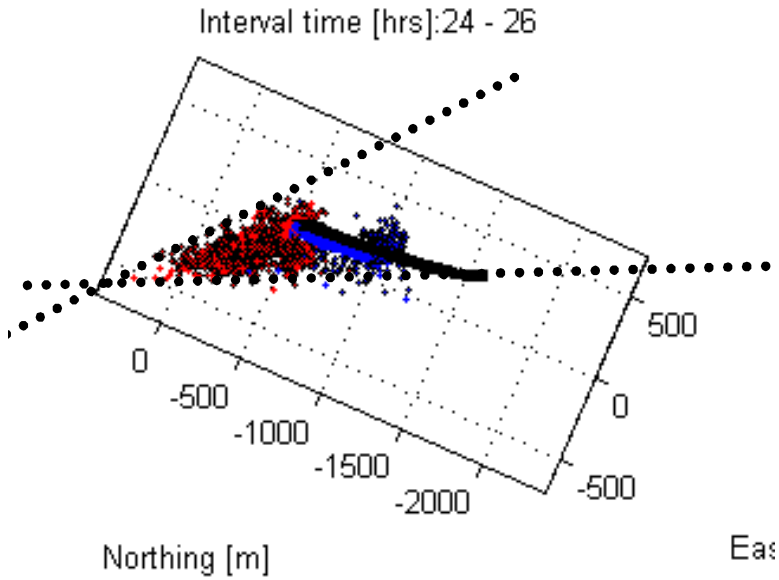
Hydraulic Stimulations and Microseismicity

- GPK2 Stimulation (July 2000): 14'080 events
- GPK3 Stimulation (July 2003): 21'600 events
- GPK4 Stimulation (September 2004): 5'753 events
- GPK4 Stimulation (February 2005): 2'966 events
- GPK4 1st Step rate test (February 2005): 183 events
- GPK4 Acidization test (March 2005): 304 events
- GPK4 2nd Step rate test (March 2005): 256 events

Soultz - Microseismicity

Seismic Events at GPK2 and GPK3 after 1 day injection

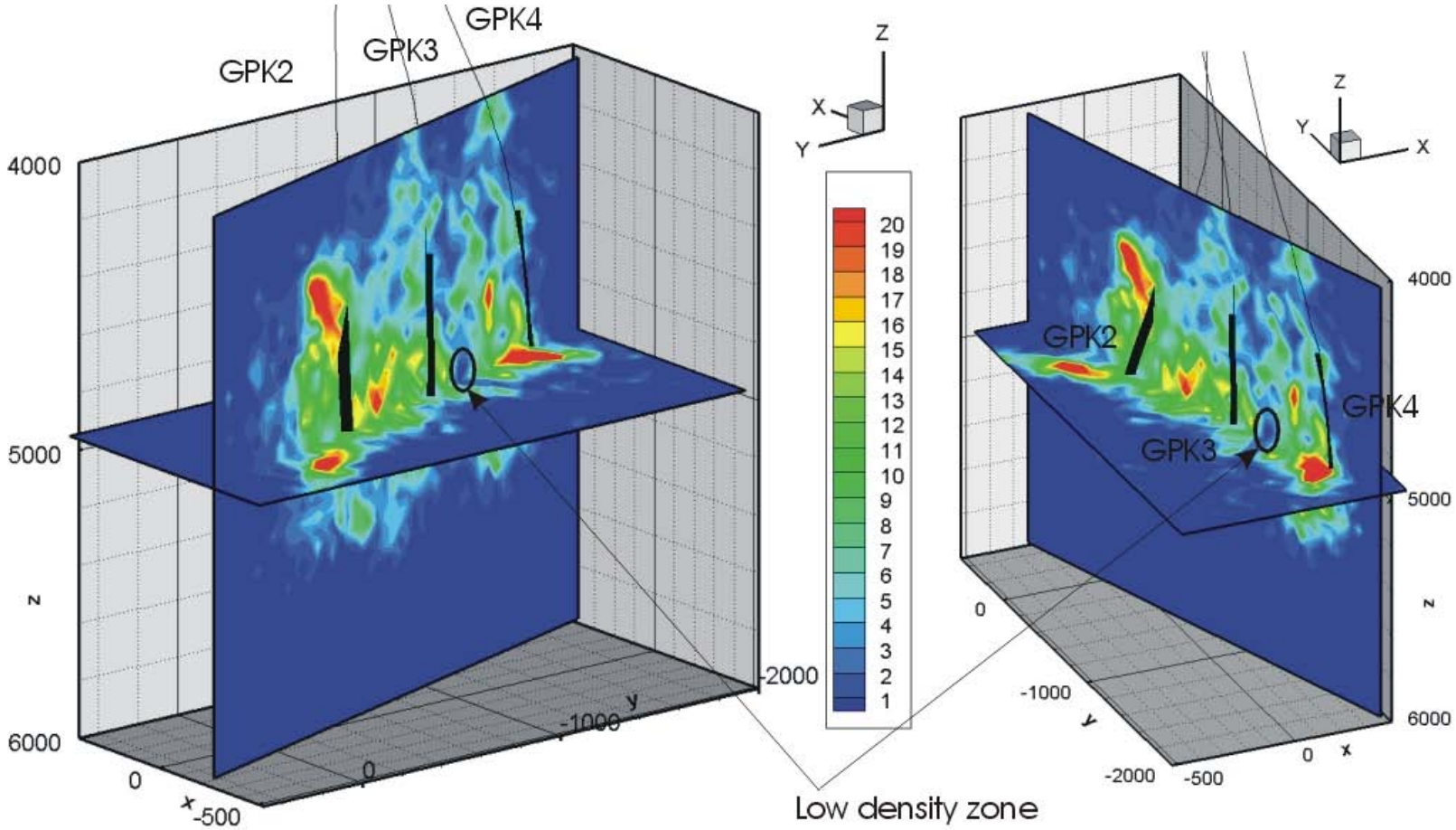




Microseismic Density

Total Stimulation Events

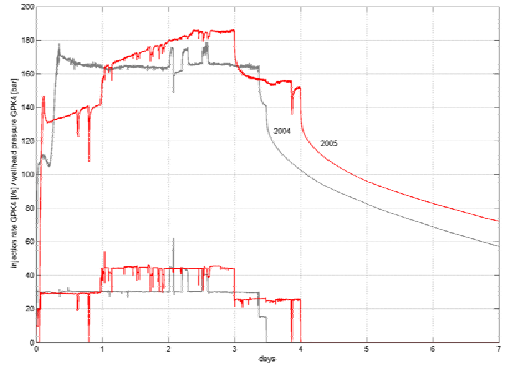
Density calculated for cube volumes: 50x50x50m^3

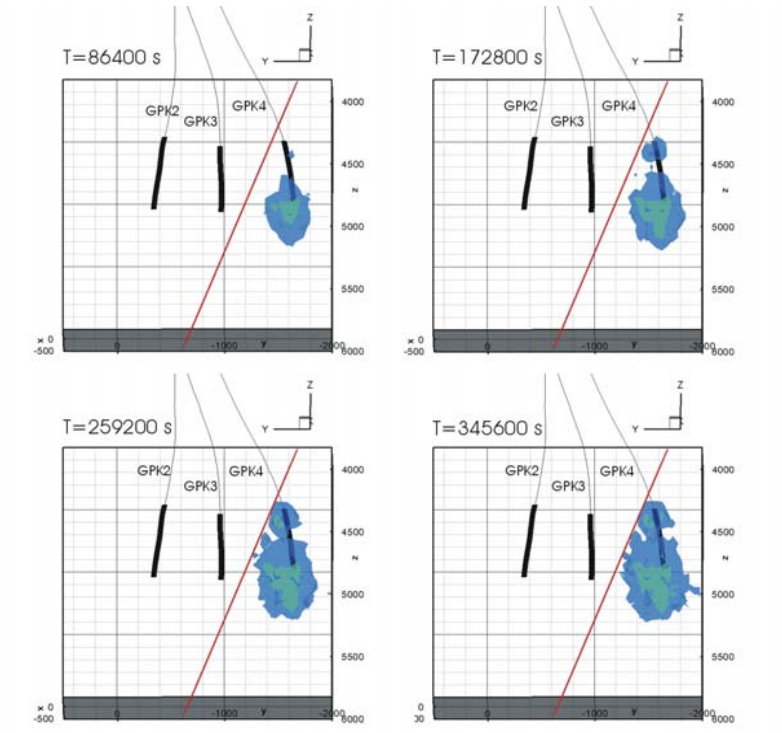


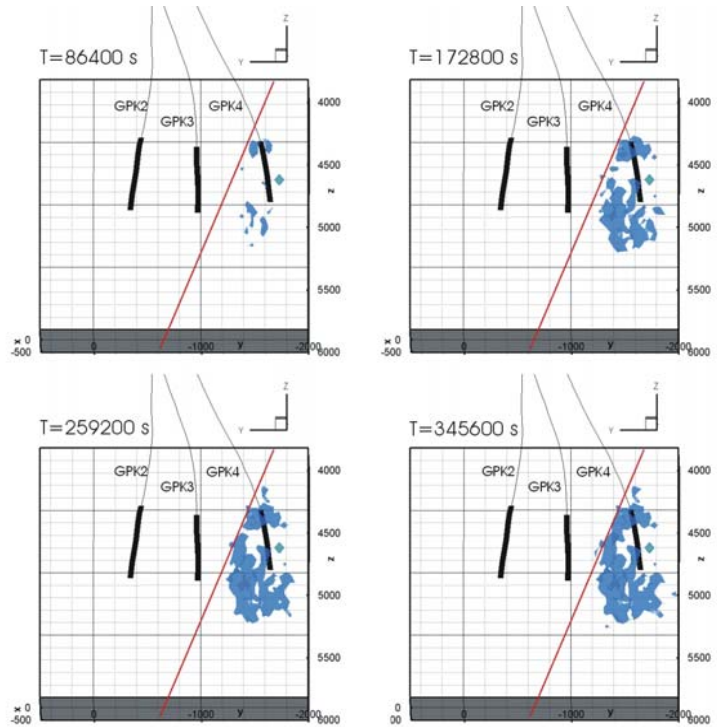
Analysis of Microseismic Density

Comparison of GPK4 Stimulations:

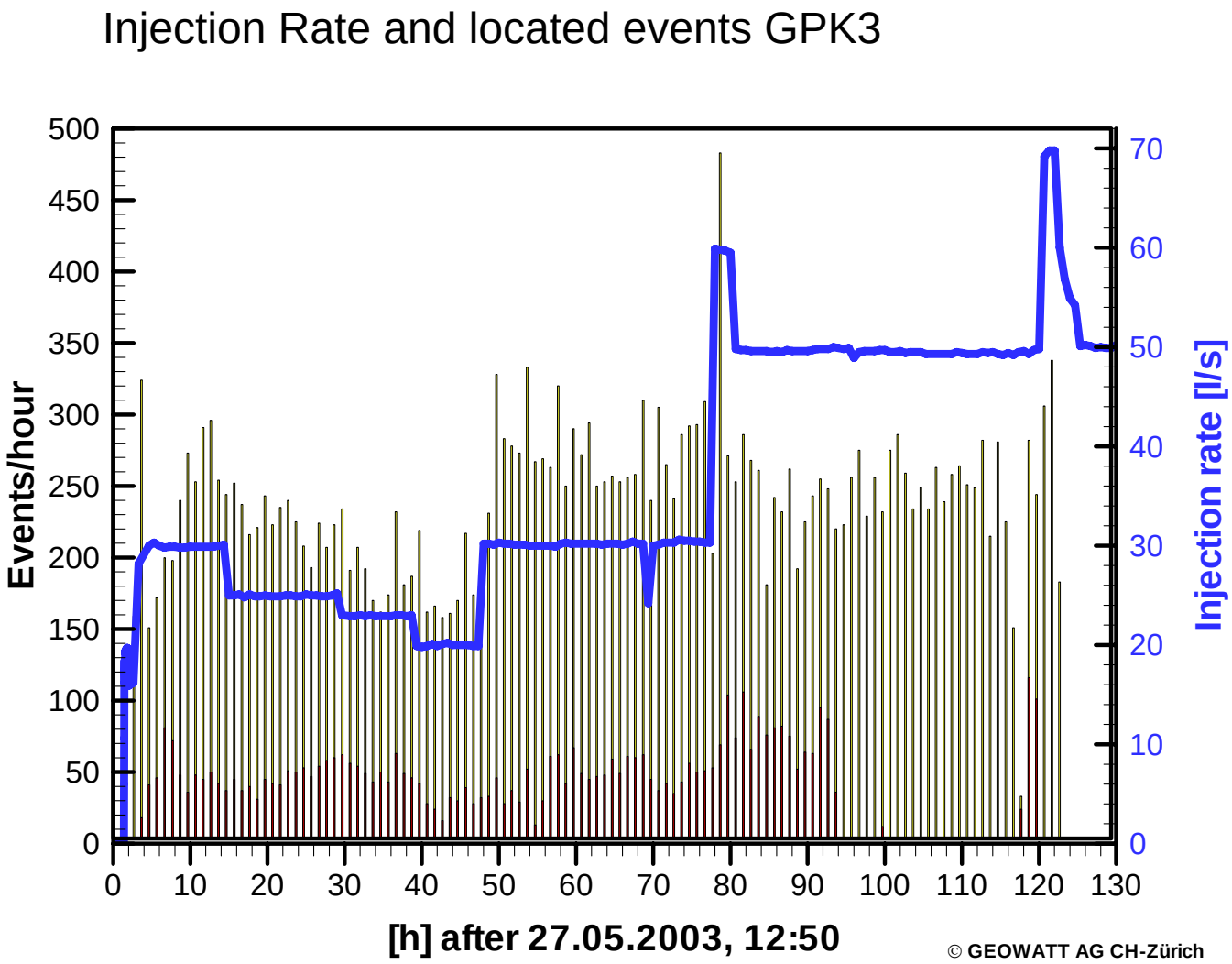
September 2004 February 2005







Indication for Hydromechanical Interaction



Stochastic vs. Deterministic Reservoir Models

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Deterministic Reservoir Models

+ Control of all physical processes
- Complex meshing
- Simplified geometries

Stochastic Reservoir Models

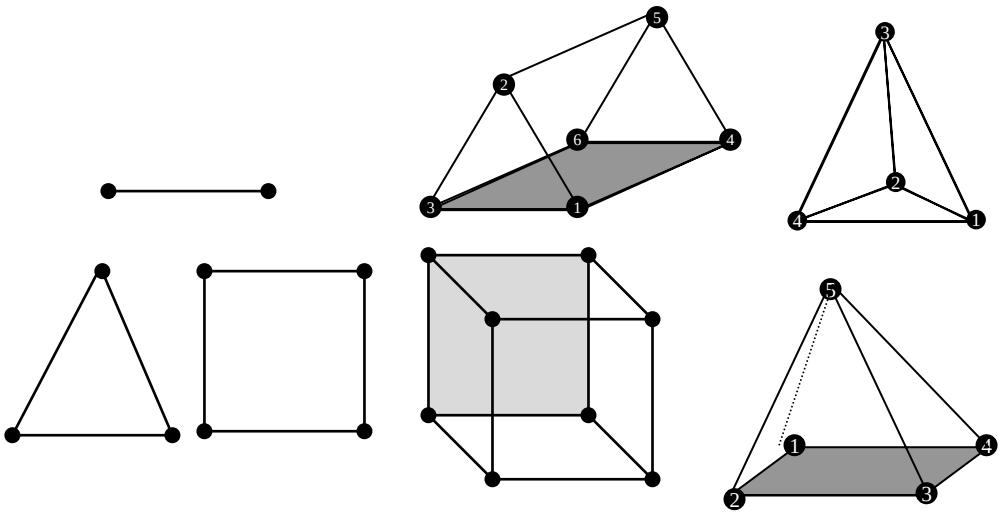
+ Refined representation of fractures/fault zones
- Neglecting often matrix interaction
- Hybrid approach

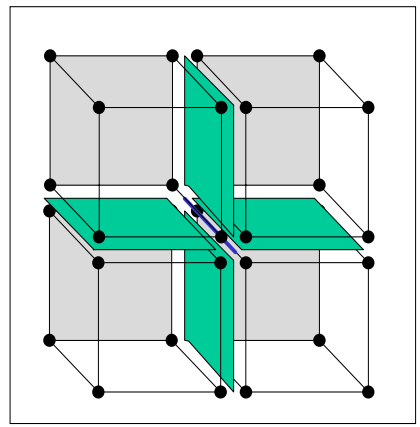
FE Code Kernel

ORIGINAL GOAL:

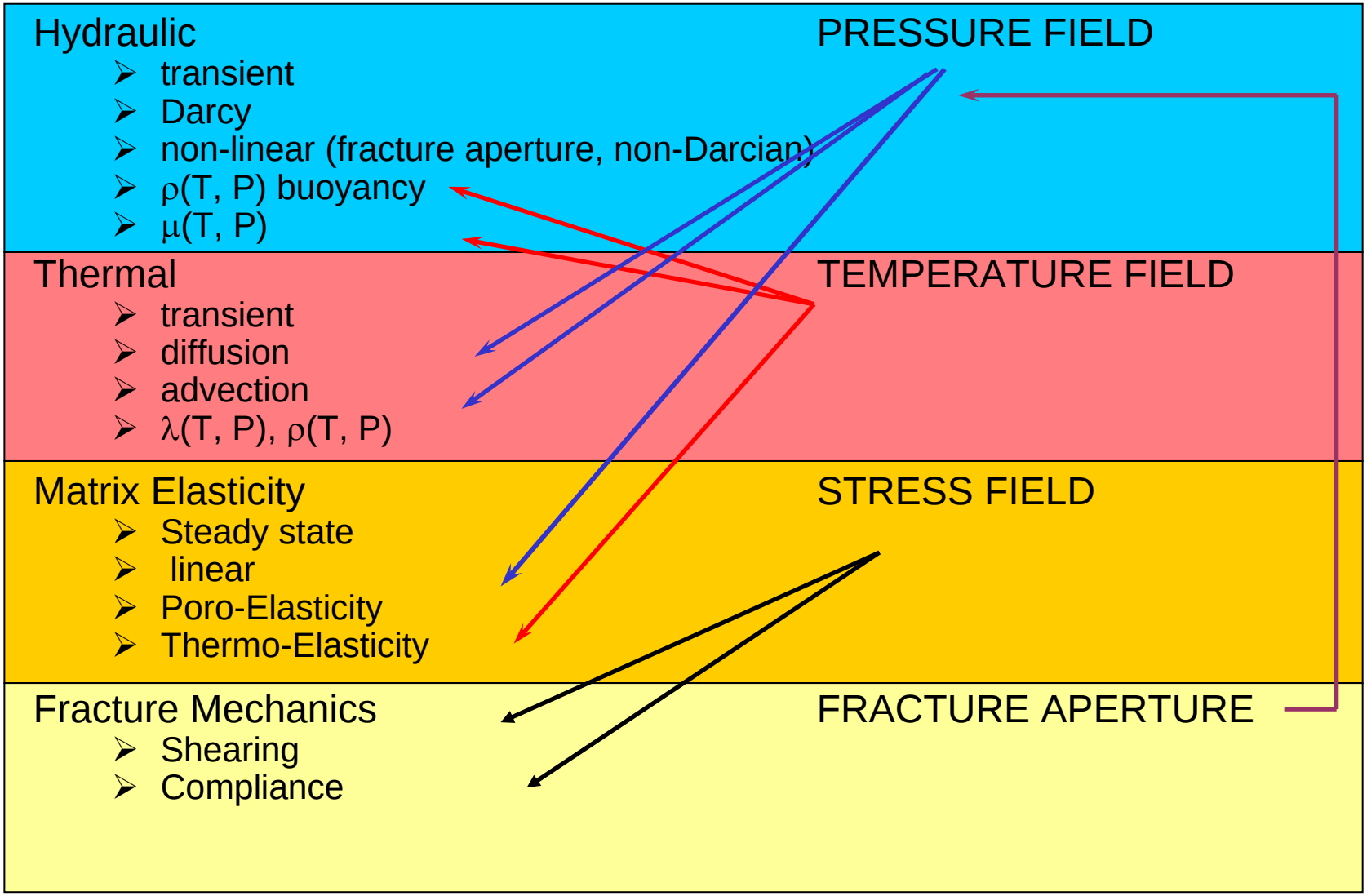
Simulation of coupled thermal-hydraulic-mechanical interactions

- fully 3-D
- very versatile code (i.e. transport of radionuclides, chemical subst.)
- continuously new (linear & non-linear) mechanisms (i.e. turbulence)
- special treatment of fractures
- 1-D, 2-D & 3-D elements with different shape functions
- platform independent (standard Fortran90)





FE Code Kernel: Implemented Coupling Scheme



FE Code Kernel: Elastic Matrix Mechanisms

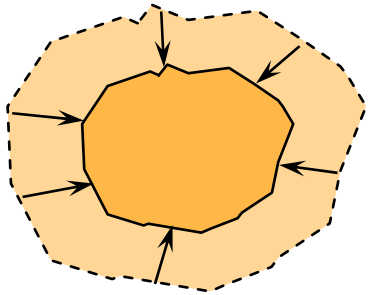
Injection of cold fluid in a hot rock matrix

Thermo-elastic matrix stresses

$$S_{ii}^{T} = 3 \cdot K \cdot \beta_T \cdot \Delta T$$

with K Bulk modulus

β_T coeff. linear expansion

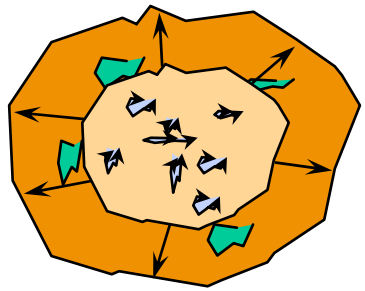


Injection of pressurised fluid in ambient matrix

Poro-elastic matrix stresses

$$S_{ii}^{P} = \alpha_B \cdot \Delta P$$

with α_B Biot coeff.

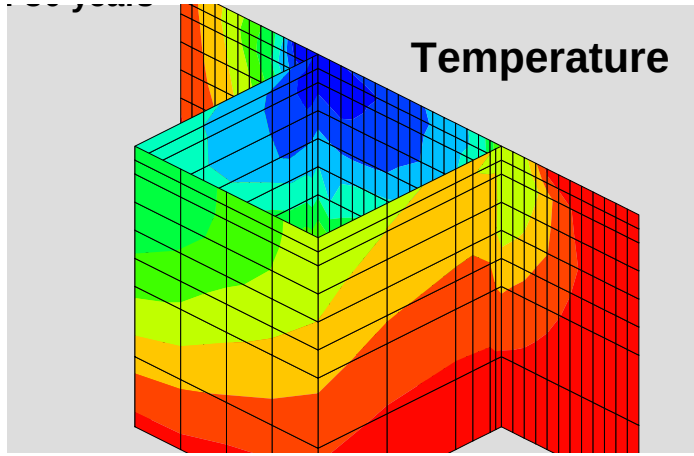


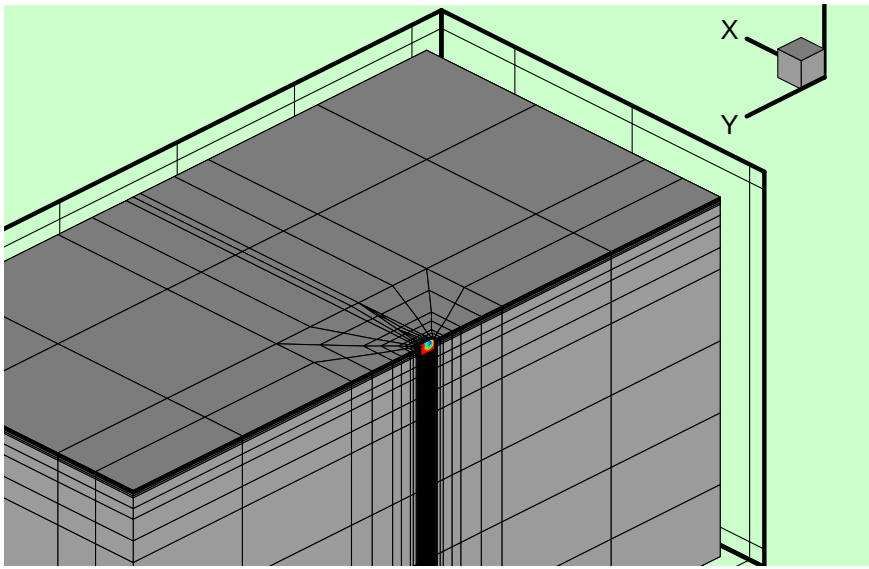
Experience on deterministic H-T-M simulations

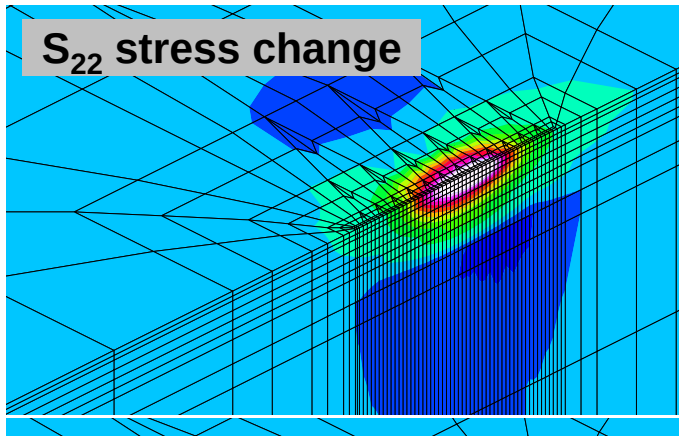
3D Reservoir

- 4 fracture zones
- Poro-Elasticity & Thermo-Elasticity (Kohl, 1995)
- Normal aperture compliance
- No shearing

-> not suited for hydraulic stimulation







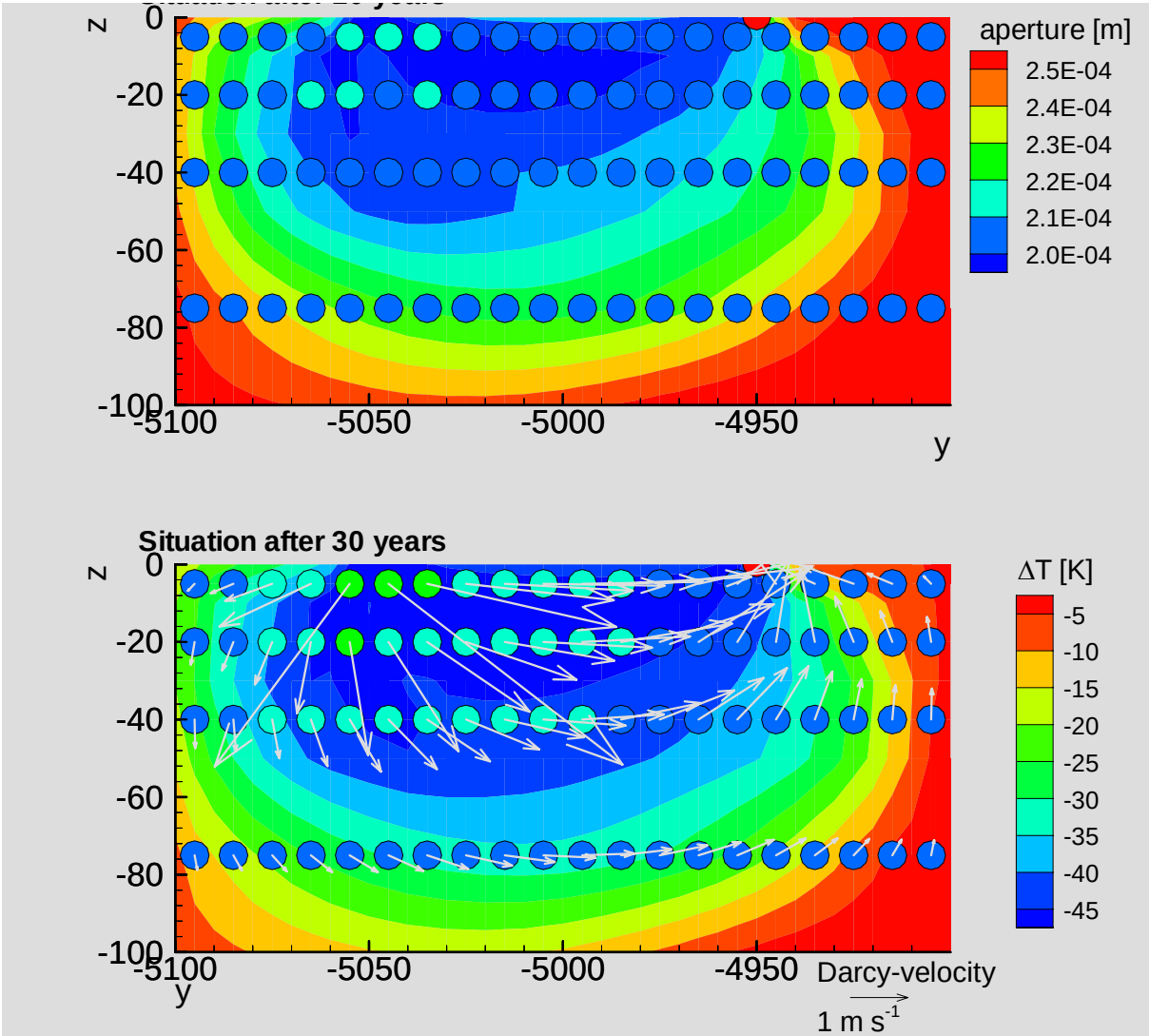
3D- Deterministic Fracture Geometry Dynamic Long Term Behaviour

Synthetic example

aperture: a_0=200μm

t=10yrs

t=30yrs



New Model: HEX-S

FE algorithm for characterization of massive hydraulic stimulations

3D simulator of hydro-mechanical processes

Coupling

- → fracture shear and compliance
- → aperture variation
- → Permeability

Mapping **deterministic** and **stochastic** fractures to FE grid

(Kohl & Mégel, 2007)

Mechanical Shearing

Penny-shaped cracks
with individual slip patches

Coulomb Shear Criteria

$$\Delta\tau = \tau - \sigma_{n,eff} \cdot \tan\left(\Phi_{basic} + \Phi_{dil}\right)$$

$$U = \Delta\tau / K_s \; ; \quad a_S = U \cdot \tan\left(\Phi_{dil}\right)$$

Compliance

$$a = \frac{a_0}{1 + 9 \cdot \sigma_{n,eff} / \sigma_{n,ref}}$$

Jacking Aperture: $\sigma_{n,eff} < 0$

Hydraulic Flow in fractured medium

Full 3D transient hydraulic model

Discretization of borehole with 1-D elements

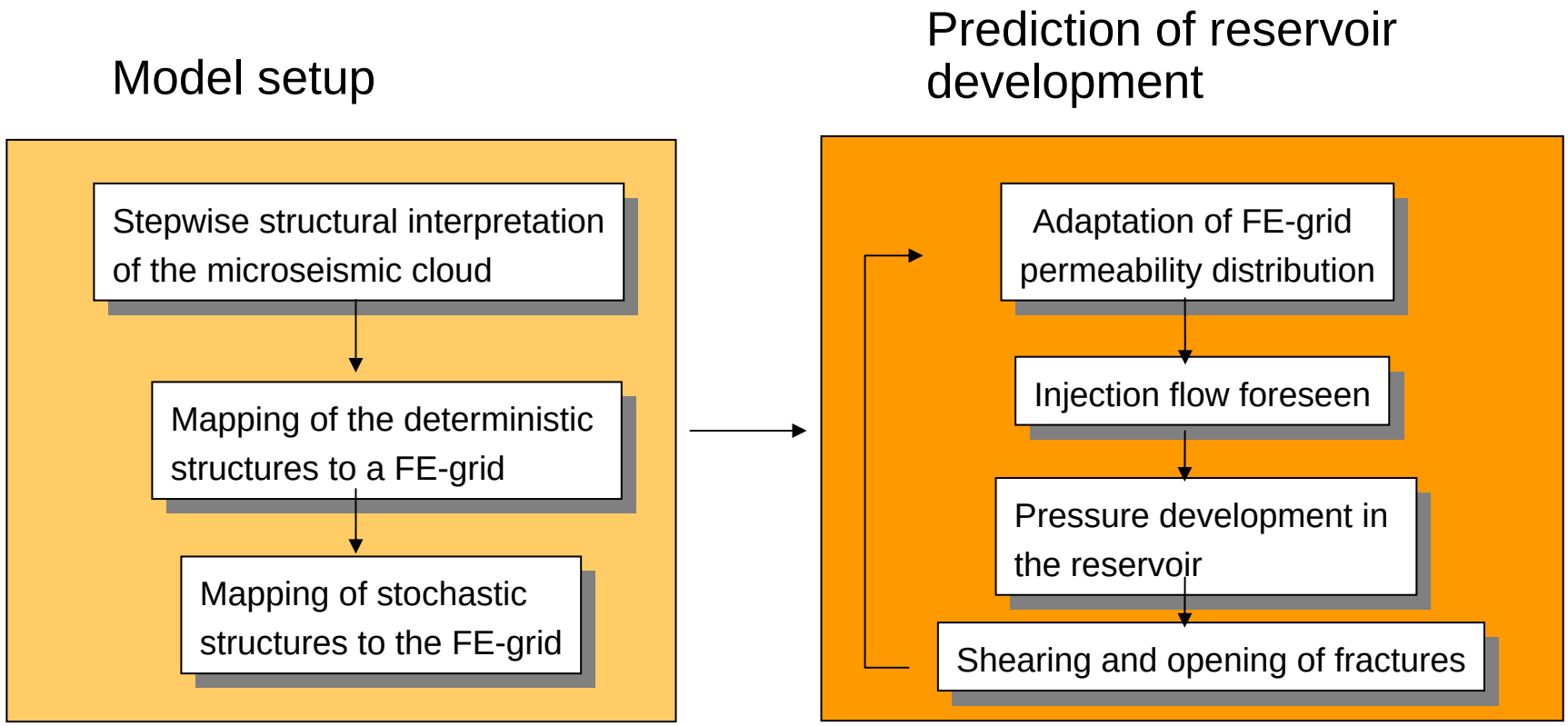
Mapping of fracture to rock matrix

explicit permeability adjustment

required hydraulic boundary conditions

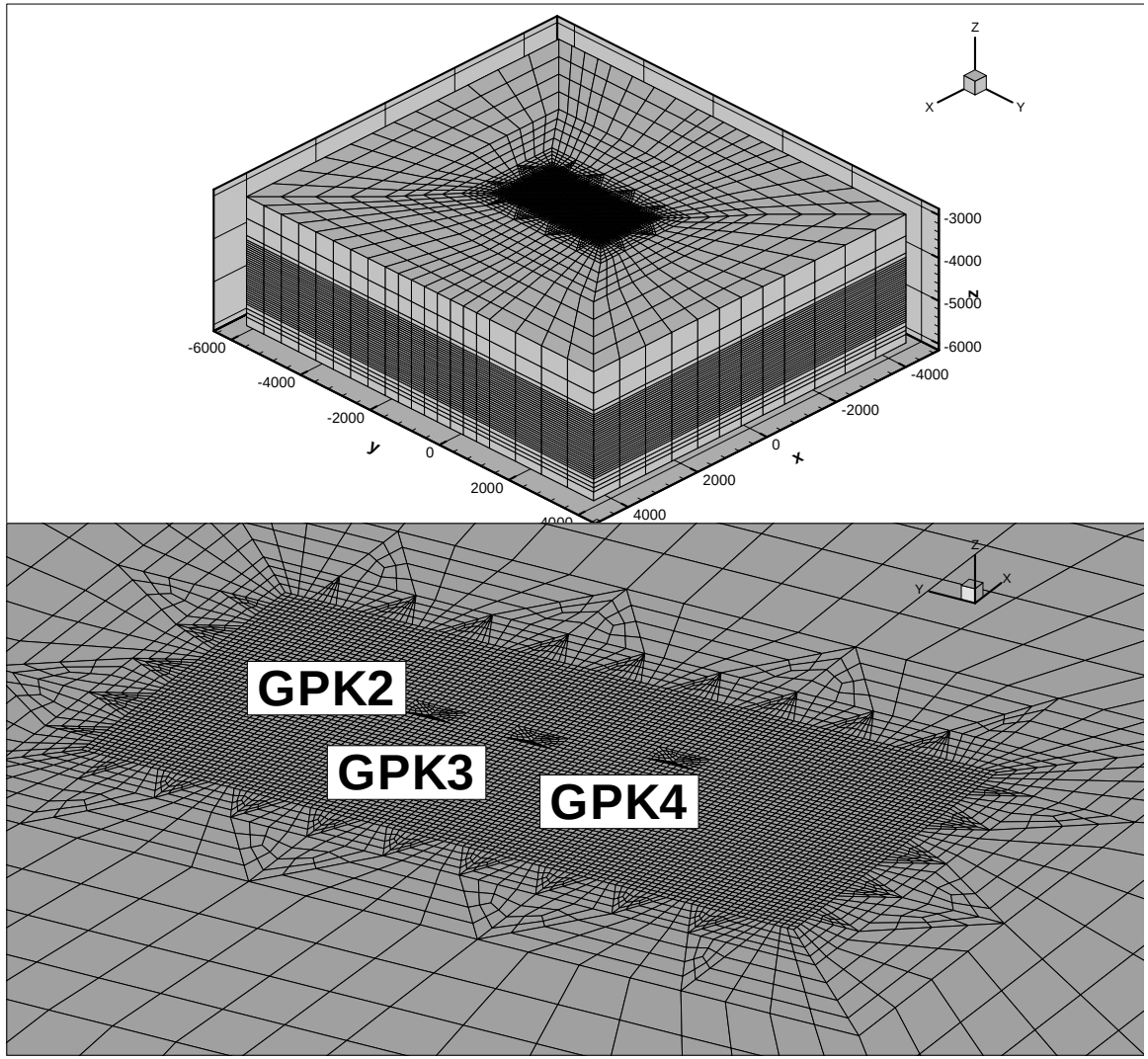
(here laterally)

'HEX-S' Flow Chart



Discretization 5km Reservoir

Numerical FE Grid
Element size 25m
~400‘000 elements
Depth: 3000-6000 m
Vertical OH-sections
Lateral borders: Dirichlet BC



Fracture Data

Deterministic Borehole Data

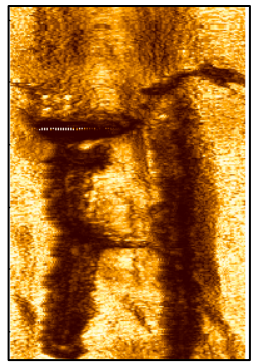
- **GPK2:** Only incomplete UBI measurement to 6 major fracture zones according to BRGM interpretation.
- **GPK3:** 11 major fracture zones from UBI log (BRGM)
- **GPK4:** 11 major fracture zones from R. Maurer

Deterministic fractured zones

4 major planes (1. Interpretation)

Stochastic fractured zones

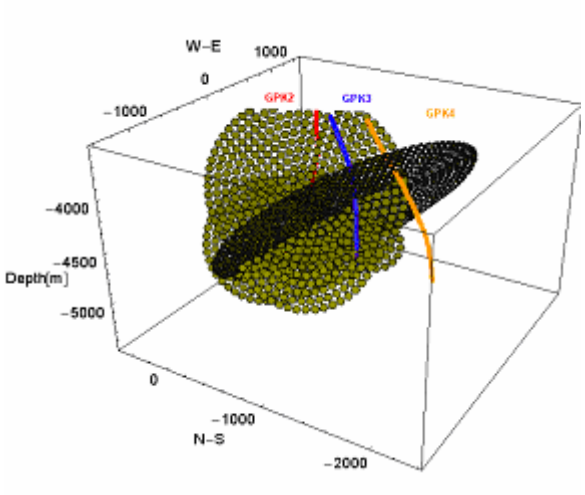
>2000 distributed planes



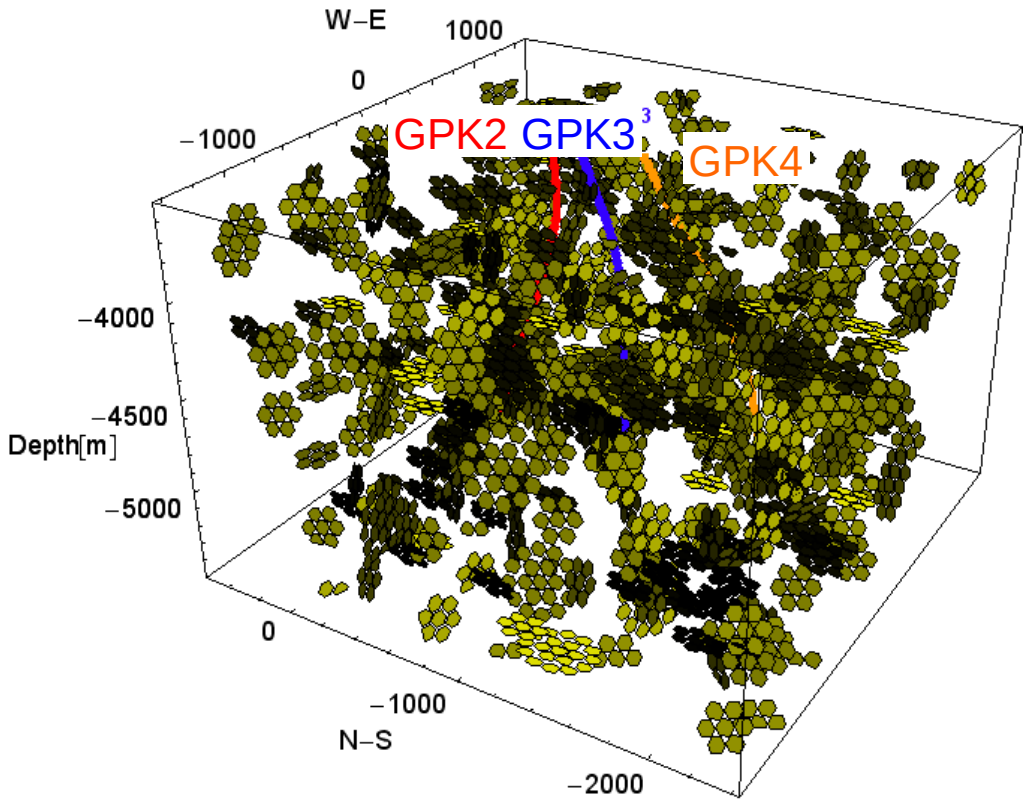
111,5	-956,8	-4517,4	122/66
111,5	-956,8	-4517,7	124/61
111,5	-957,1	-4542,3	330/54
111,5	-957,1	-4542,6	320/54
111,4	-957,3	-4569,1	307/60
111,7	-960,4	-4660,0	266/52
112,2	-962,3	-4685,9	065/68
112,3	-962,7	-4691,7	247/67
112,3	-962,7	-4992,8	249/40
111,8	-968,2	-4943,0	292/58
111,2	-966,7	-4971,3	356/48
280,6	-1590,0	-4635,0	275/73
282,1	-1596,5	-4666,4	285/73
282,8	-1600,3	-4683,6	275/77
284,7	-1610,3	-4732,6	315/70
287,1	-1623,3	-4826,3	255/74
287,3	-1626,2	-4847,0	270/76
287,6	-1632,0	-4886,9	250/67
287,7	-1637,1	-4920,8	070/68
287,7	-1638,3	-4929,0	350/75
287,7	-1640,8	-4944,4	285/75
287,6	-1641,3	-4947,2	280/74
33,5	-438,7	-4394,8	250/70
11,8	-419,5	-4458,5	70/70
-6,4	-408,4	-4525,1	70/70
-53,7	-376,6	-4716,8	250/65
-79	-355,9	-4816,5	250/65
-108,5	-337,8	-4936,6	250/70

Soultz Fracture Model

Deterministic slip patches



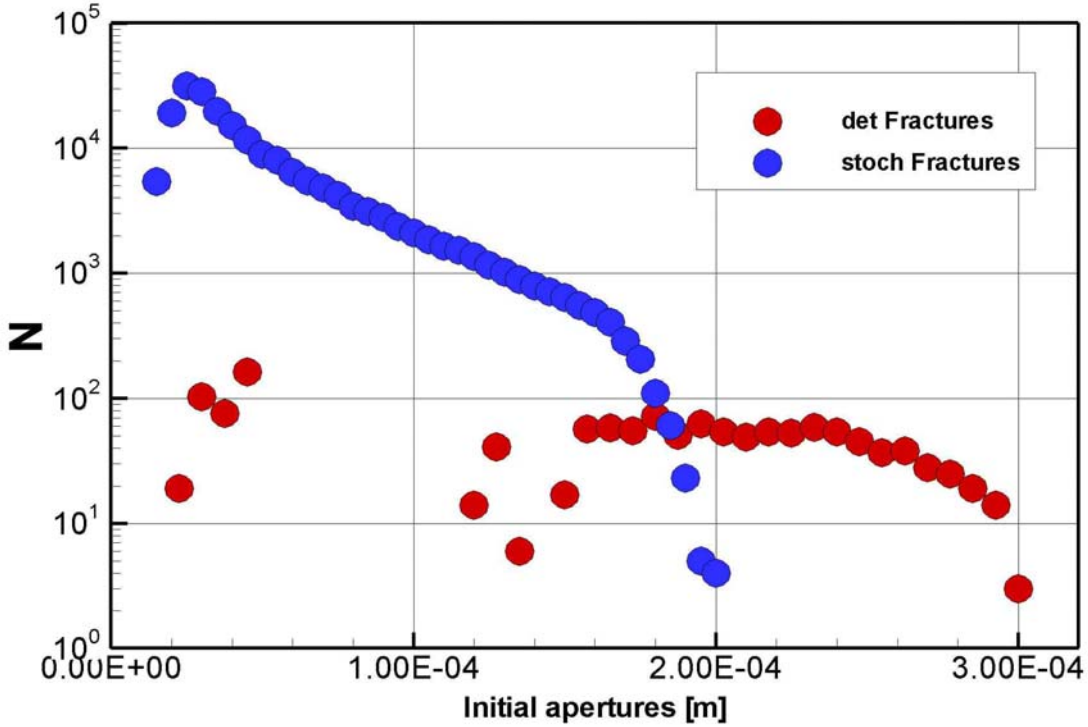
Stochastic realization



Initial apertures: Deterministic / stochastic slip patches

Aperture:

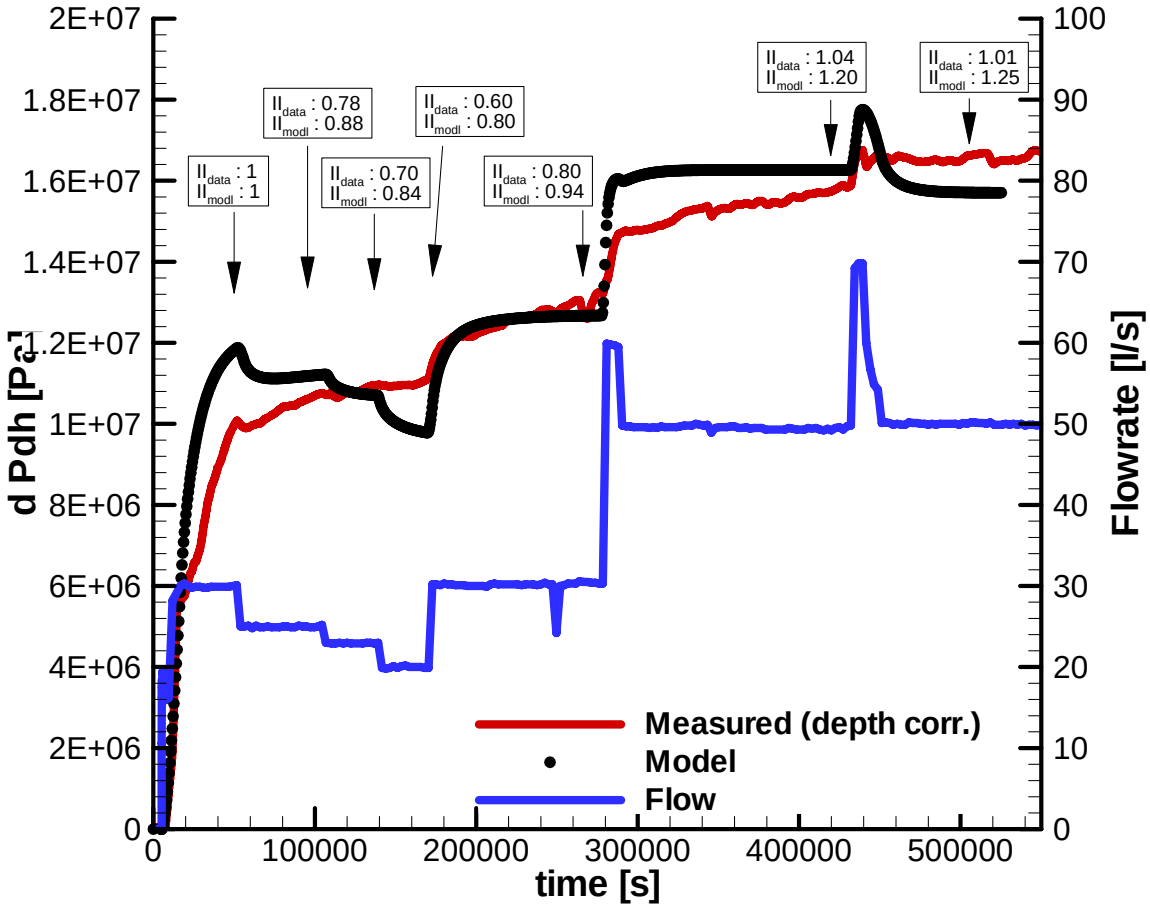
- "stochastic" slip patches: 20 – 300 μm
- "deterministic" slip patches generally larger
- Depending on orientation and depth (stress field)
- Calibrated with initial borehole transmissivity



First Assessment
GPK3 Stimulation

Stimulation GPK3

Focus on major hydraulic injection steps

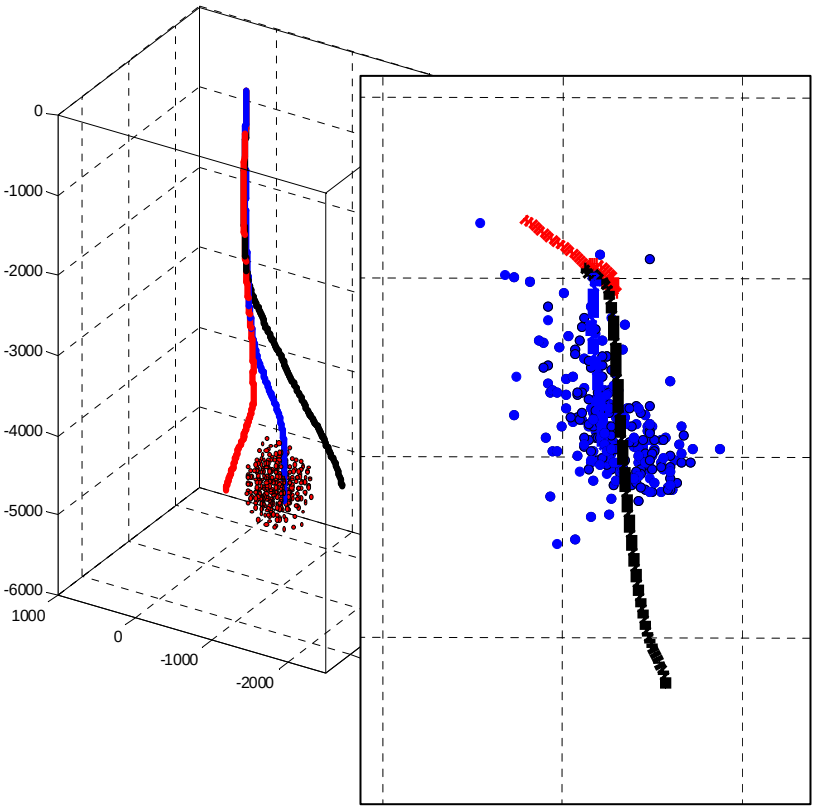


- Fit of downhole pressure history
- Highly non-linear processes
- Permeability variation due to shearing

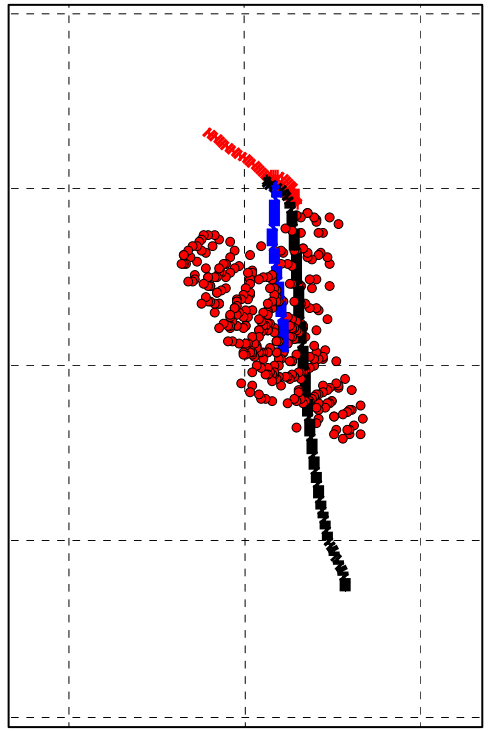
Identical time constants

Dynamic reservoir processes

Microseismic events GPK3



Simulated shearing GPK3

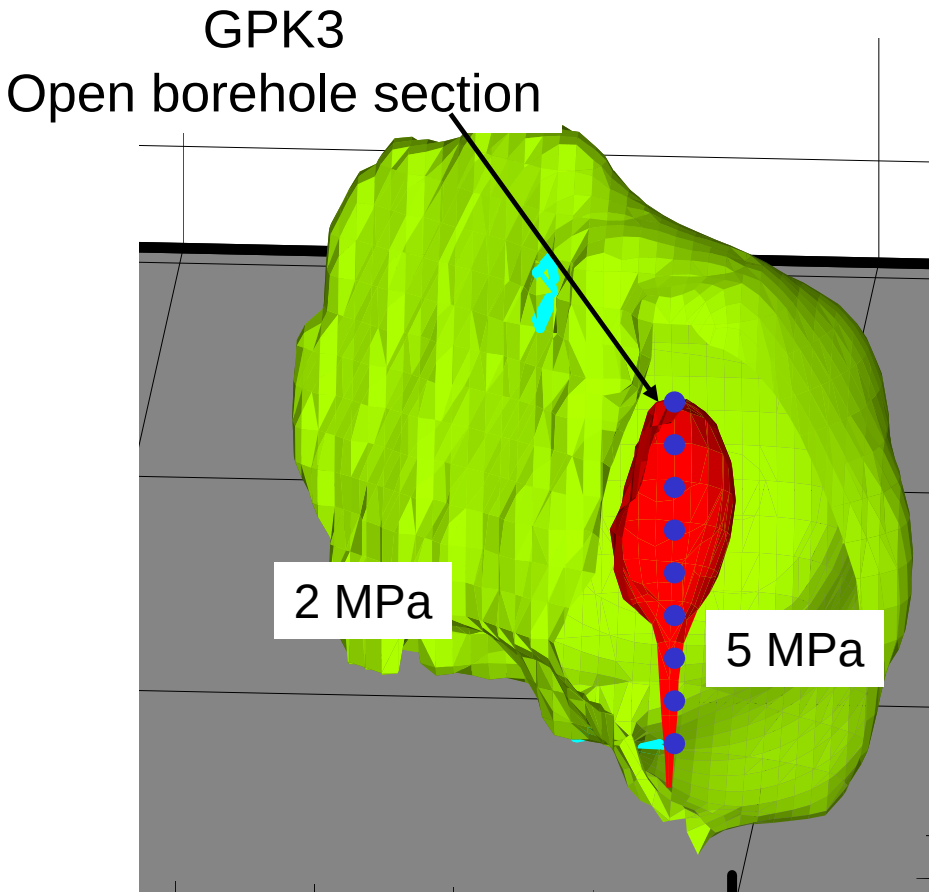


t =1 day

Identical spatial constants

Soultz 3D Hydraulic Field

Pressure distribution around GPK3



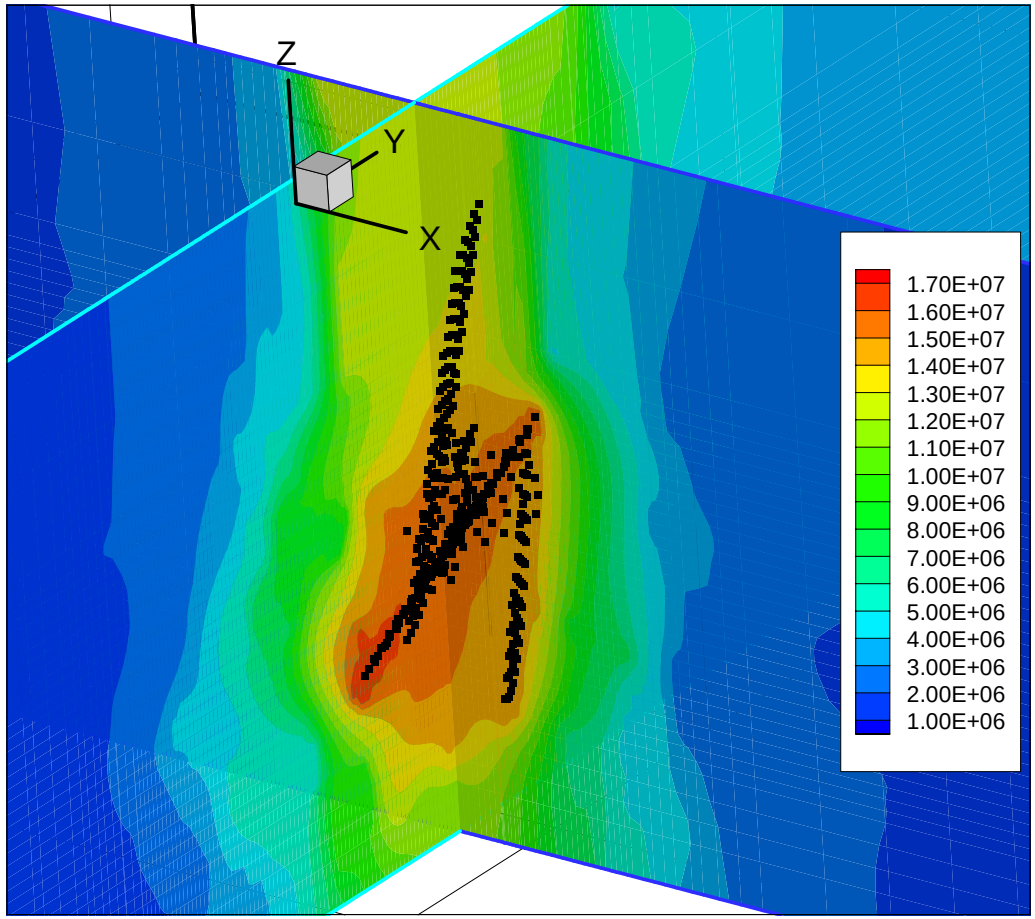
- Strongly anisotropic pressure distribution
- Radial field only around injection point
- Pressure envelope oriented along fracture orientation
- Pressure wave propagation in areas with highest degree of fracturation

Reservoir Pressure Distribution

Simulated shearing events & pressure distribution GPK3

Flow aligned along seismic structures

Seismicity connected to zones of high pressure



Modeling Tool HEX-S: Prognosis GPK4 stimulation 04SEP13

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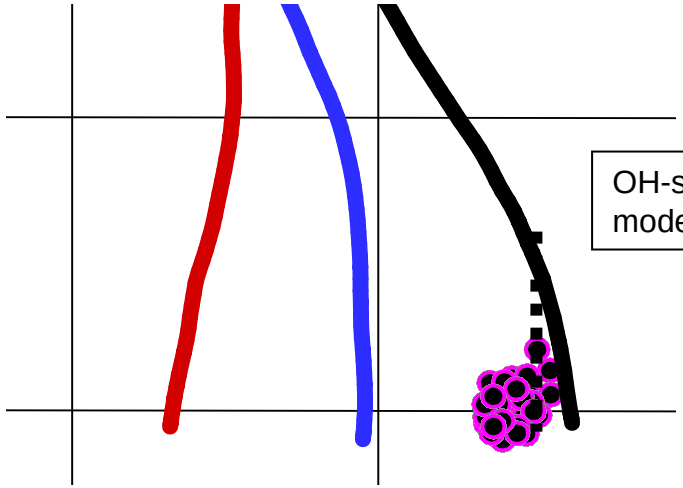
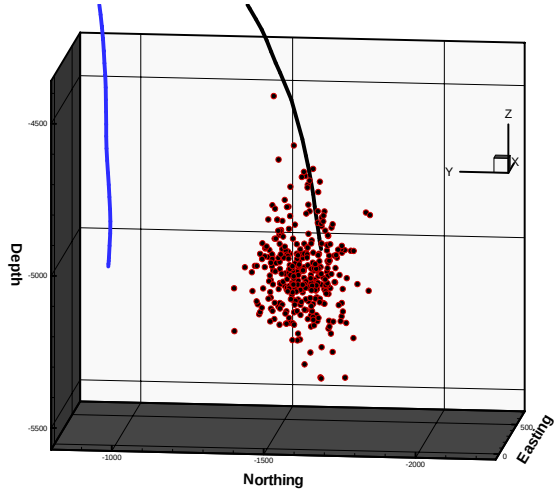
Forecast

- 10h

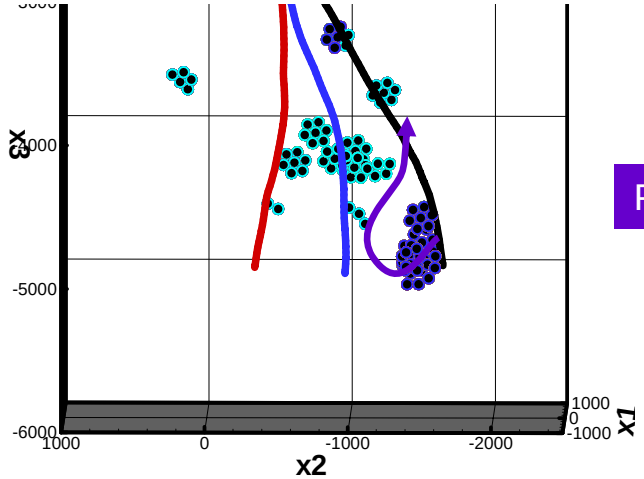


OH-section model

Measurement



- 1st Day



Path of development

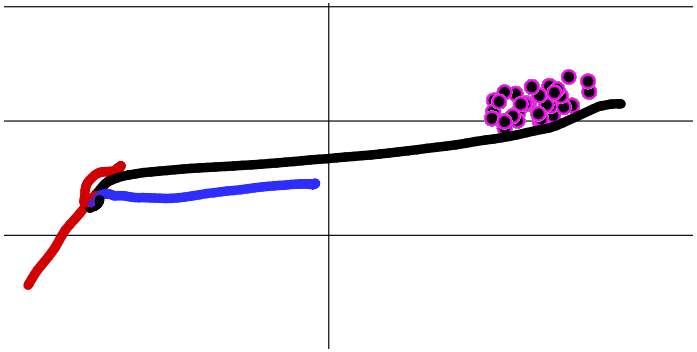
Forecast GPK4 stimulation: HEX-S Hydraulic Model

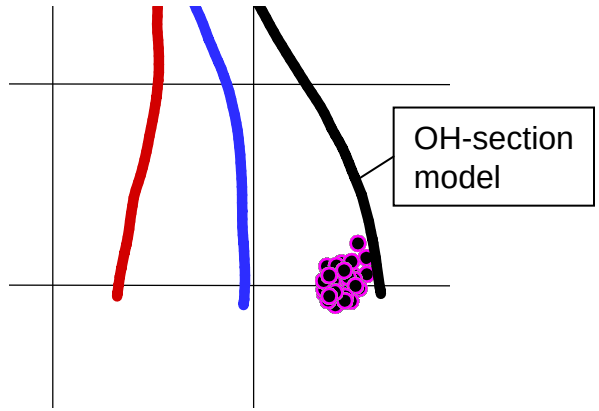
Predicted evolution of shearing events at GPK4 after

Plane View

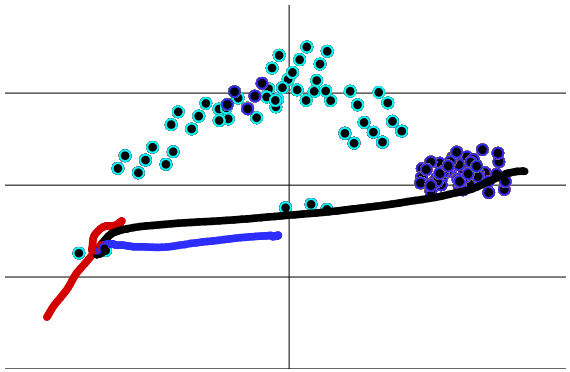
View from West

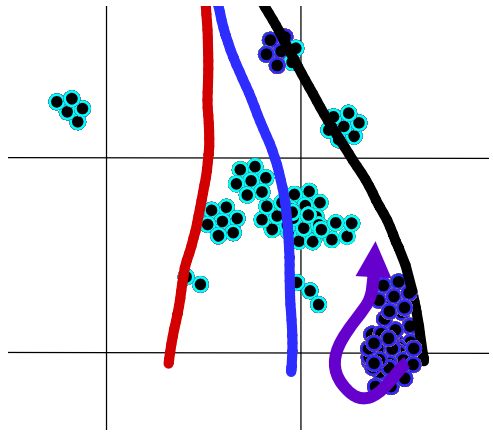
10 hrs stimulation





1 day stimulation



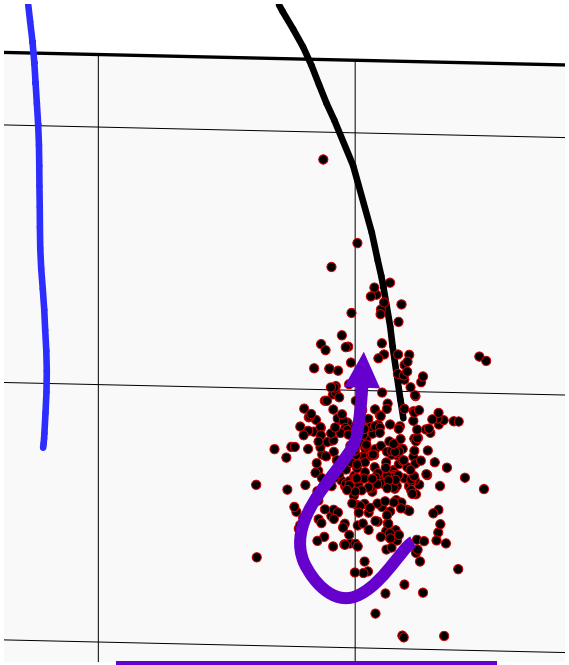


Events are not location-corrected

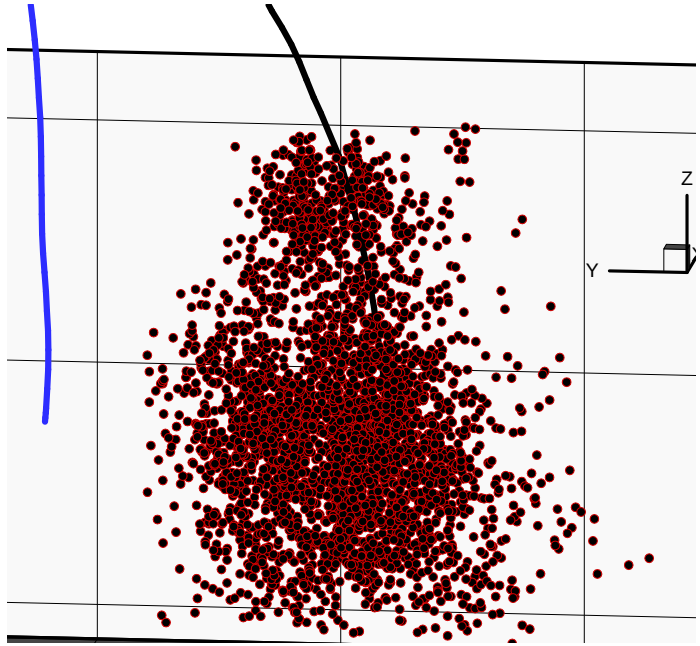
Stimulation of GPK4 (13-16 Sep. 04) Microseismic Locations

Measured evolution of microseismic locations at GPK4

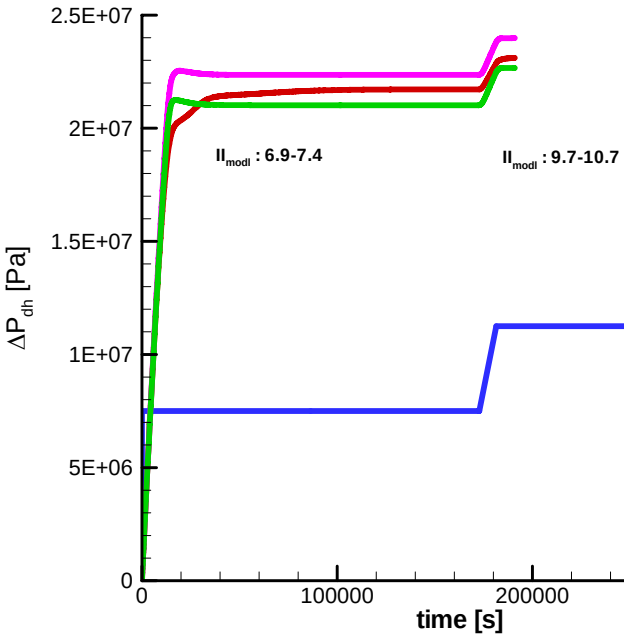
View from West: t= 10h



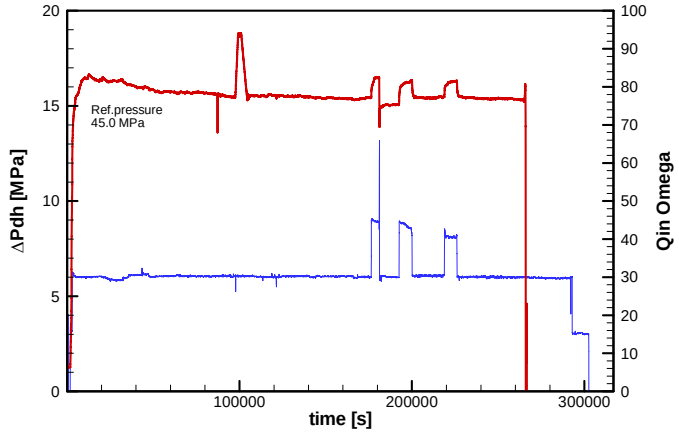
View from West: t= 3 days



Modeling Tool HEX-S: Prognosis GPK4 stimulation 04SEP13



Forecast



Measurements

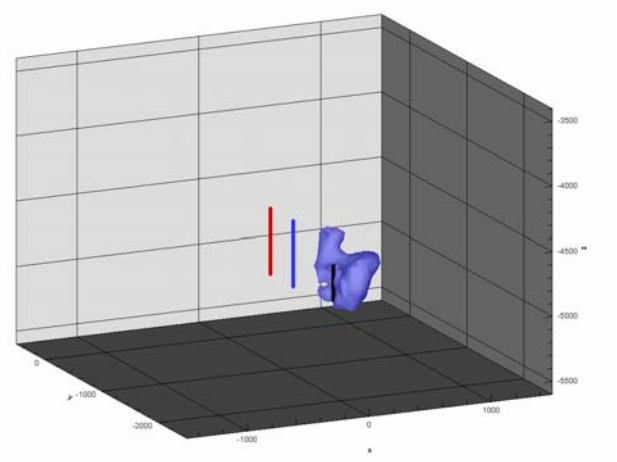
- $\Delta P_{dh} \approx 21$ MPa for 30l/s
- additional $\Delta P_{dh} \approx 1.5$ MPa when increasing to 45 l/s
- maximum P_{dh} at t=15500 s
- General characterisic: Short transient P-behaviour

- $\Delta P_{dh} \approx 15.5$ MPa for 30l/s
- additional $\Delta P_{dh} \approx 1.05$ MPa when increasing to 45 l/s
- maximum P_{dh} at t=16'600 s
- short transients

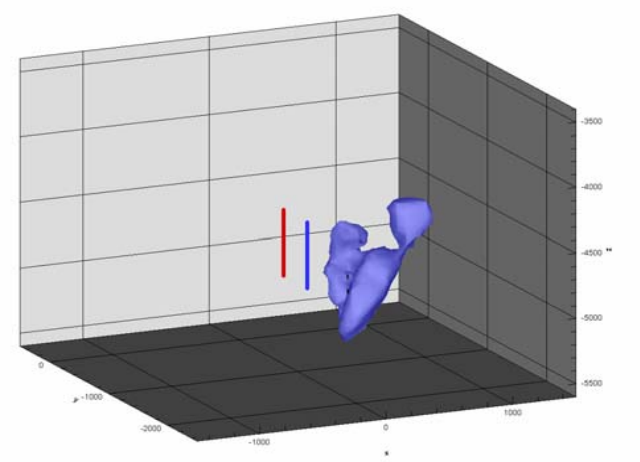
Simulation GPK4
Increase of aperture (≅permeab.)

GEOWATT AG

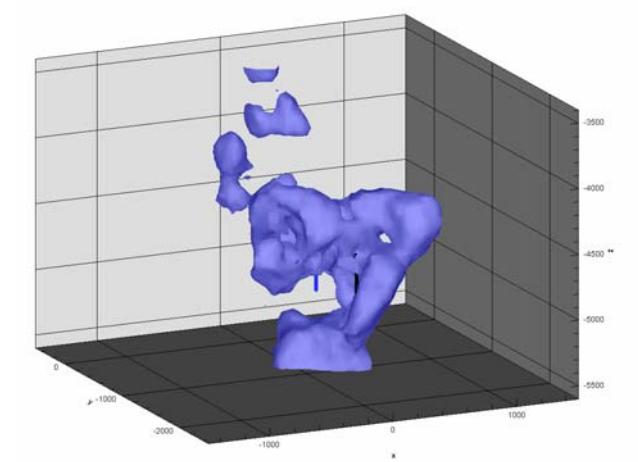
2.7 h



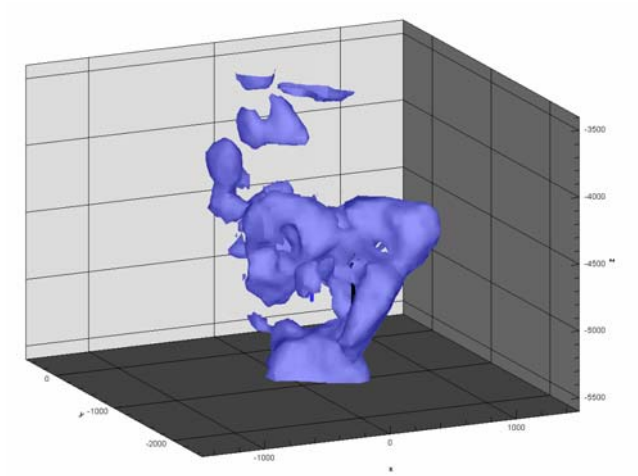
5 h



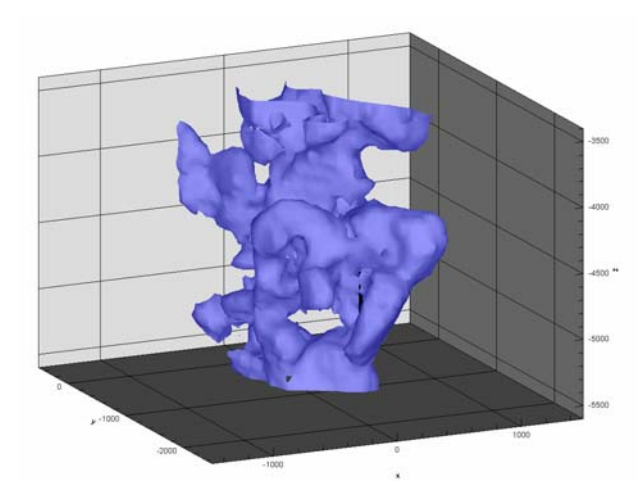
20 h



36 h



53 h



Iso-Surface = 10 μm

New fracture volume

Injection vs. Volume Change never explicitly defined

Flow injection vs. new fracture volume:

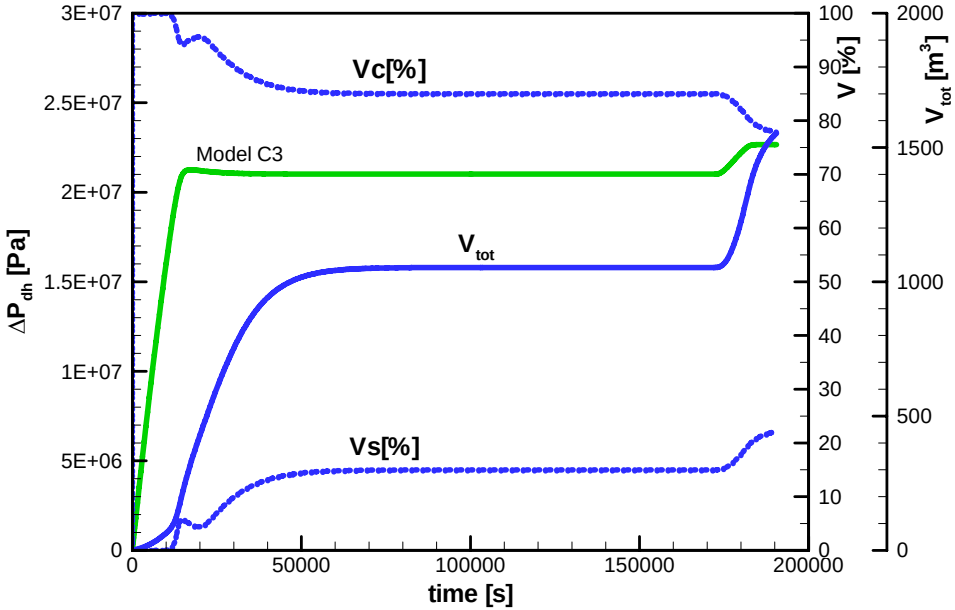
- Injection during simulation period: 6'300m^3
- Fluid losses over lateral drainage systems

Calculated Volume Change reflects data

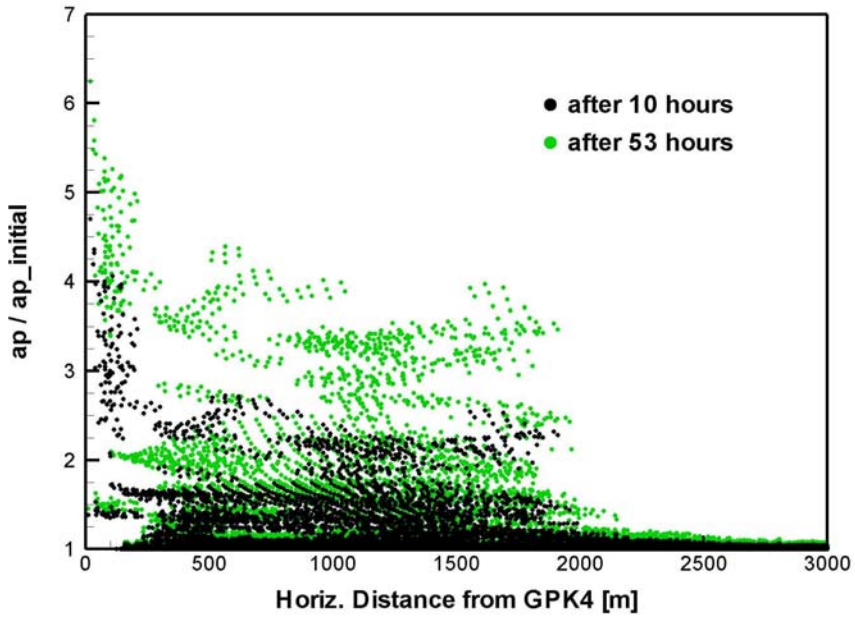
- 30 l/s injection during first 50'000 s: -> 1000 m^3
- 45 l/s during last 12'000 s -> Additional 500 m^3

80% of the new fracture volume is generated from compliance

$\Delta V(t)$



$\Delta a(r)$ at 10 / 53 hrs



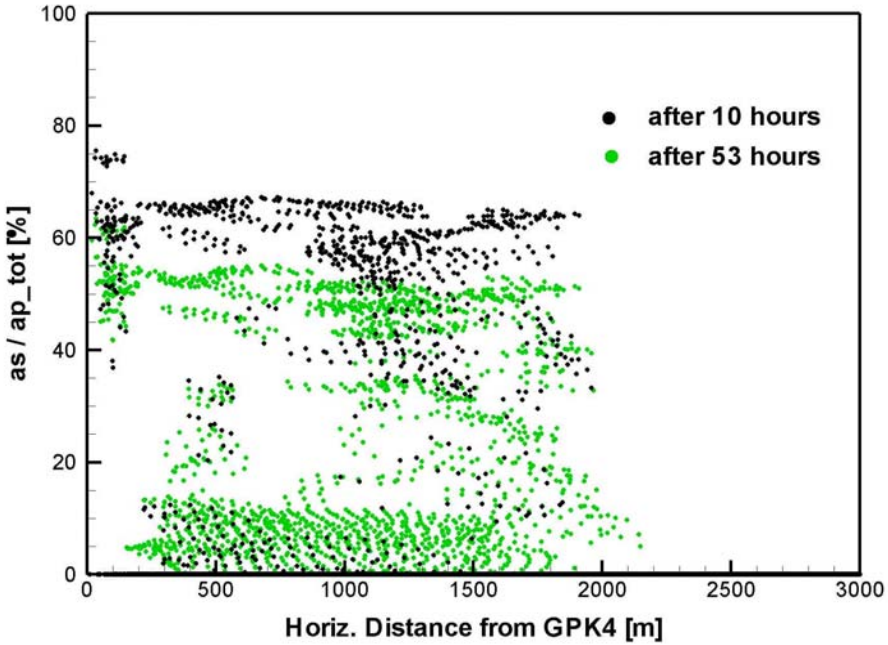
Importance Shear Failure

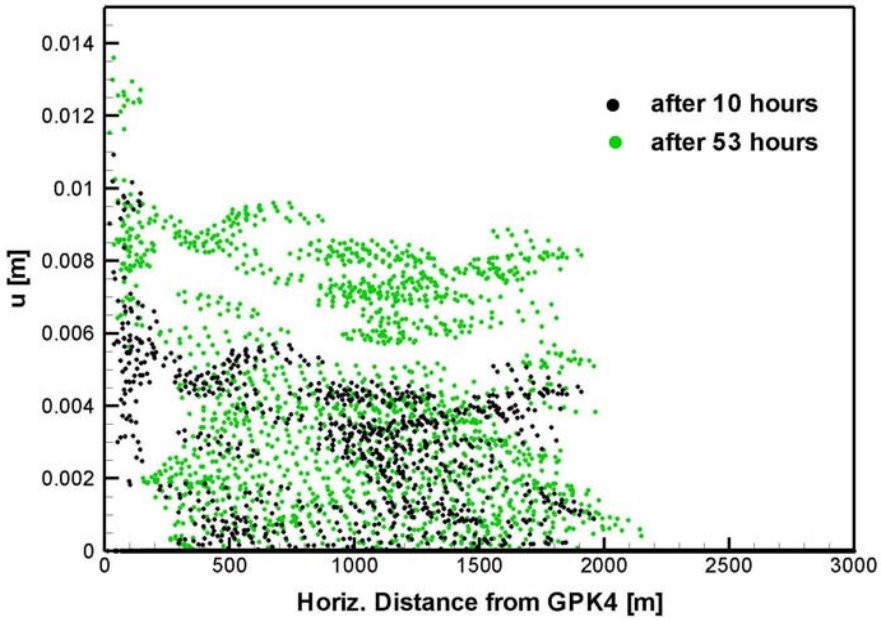
Percentage of aperture improvement

- next to the borehole: up to 70% of the total aperture enhancement.

Predicted displacements

- in reservoir: max. 1cm
- near borehole: up to 1.5cm





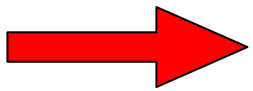
Conclusions

HEX-S new hydro-mechanical reservoir model

- Deterministic/stochastic fracture distribution
- Dynamic reservoir behavior by joint H-M solution

Requirements:

- Geological / fracture reconnaissance
- Stress field



Physical Reservoir Model
Based on integrated data analysis

<u>Successful forecast of GPK4 stimulation</u>

Future Application:

Microseismic impact

- Generic studies
  - using local reservoir properties
  - Design calculation to minimize shear displacement

Design of optimum reservoir creation strategies

- optimization of lateral seismic extension
- Dual vs. single injections

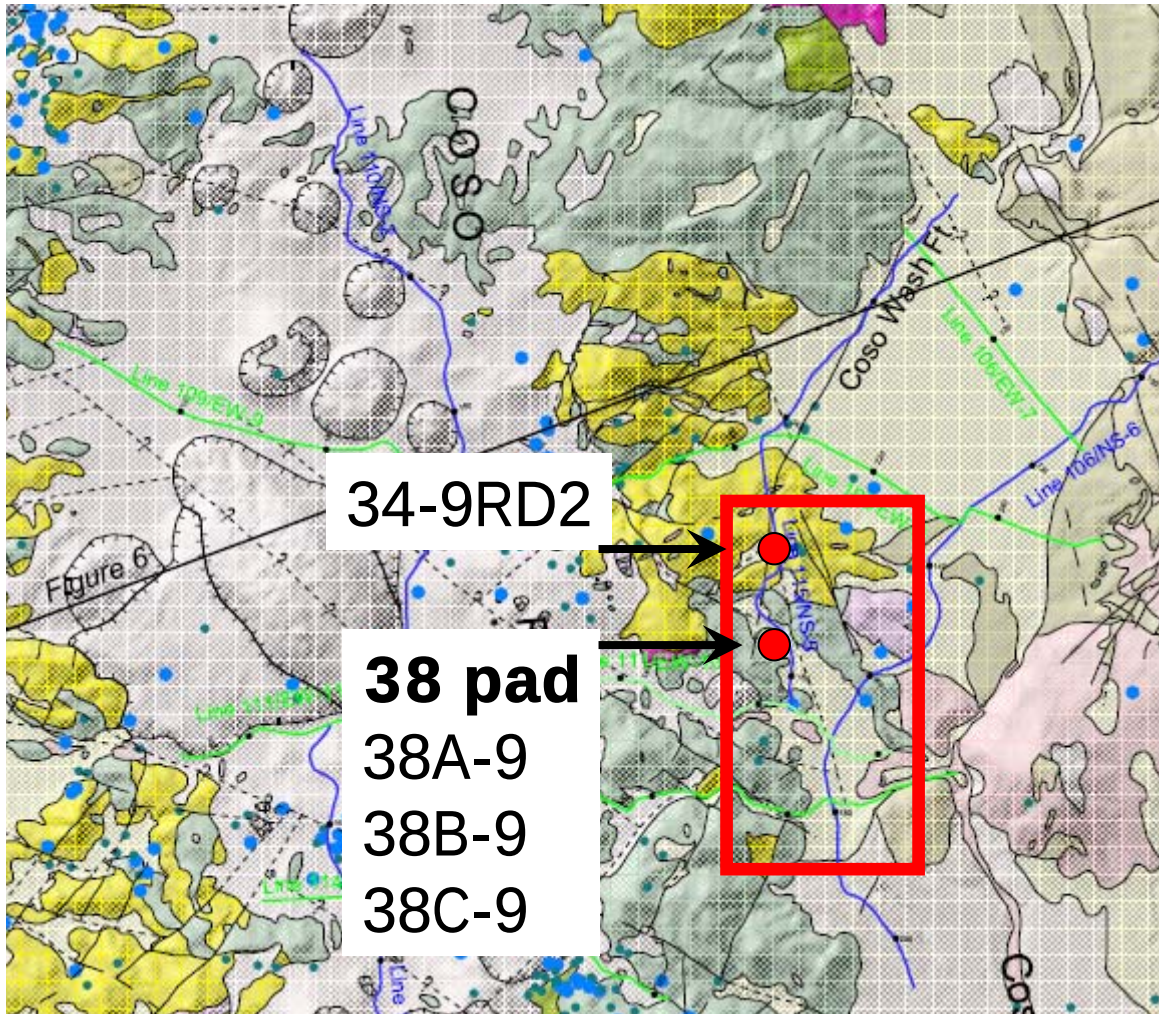
Resolve fundamental questions

- Max. flowrate vs. max. volume injection

On Site support during stimulation

- Model update jointly with seismic recording
- Minimizing test duration

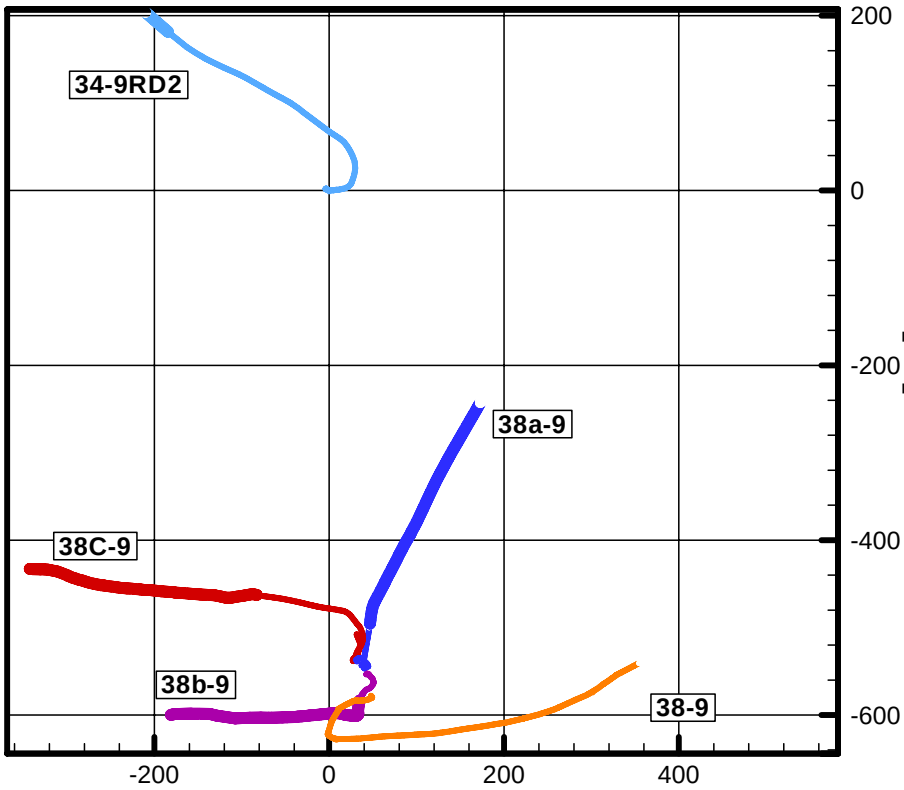
Coso Project Area



Coso EGS site

Borehole trajectories

open hole section (thick lines)

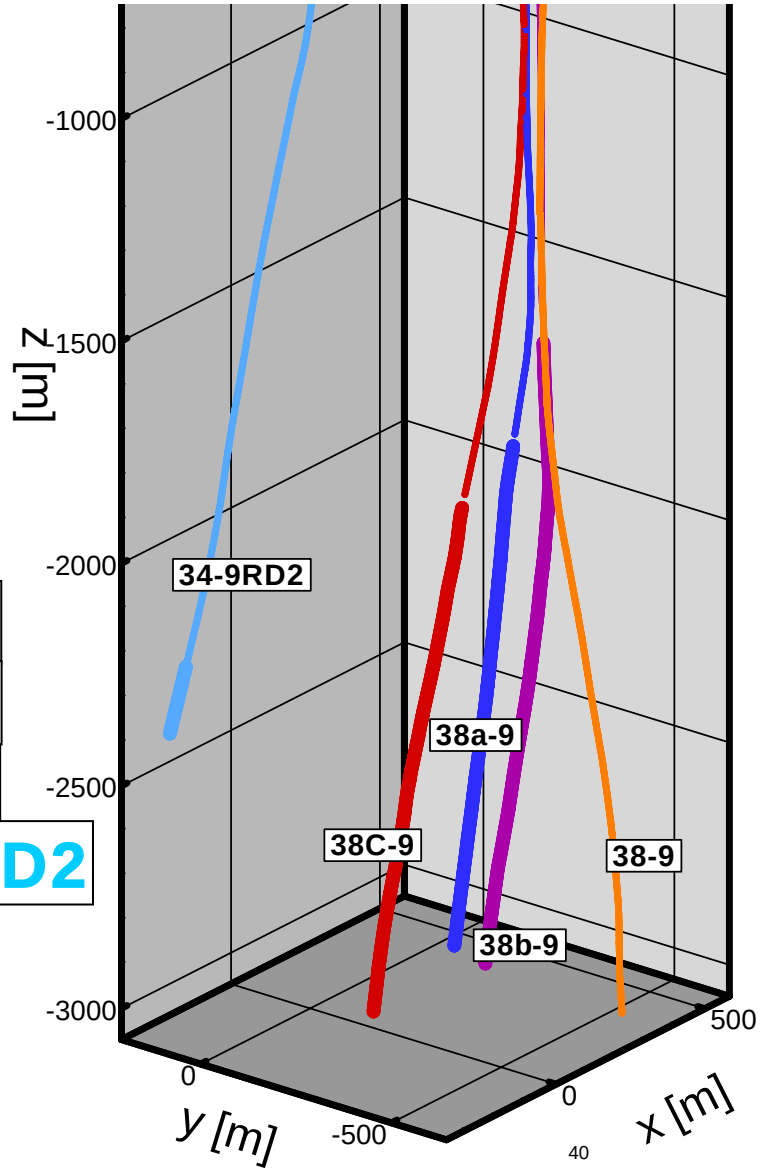


38A-9

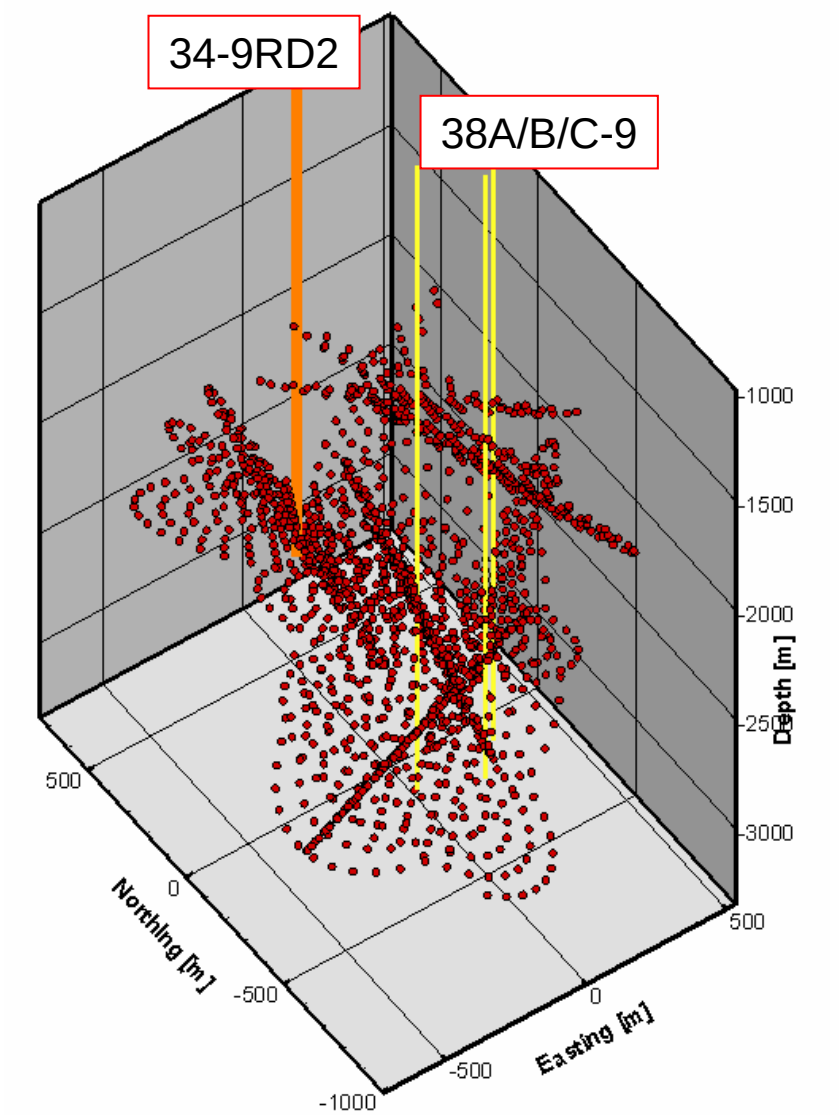
38B-9

38C-9

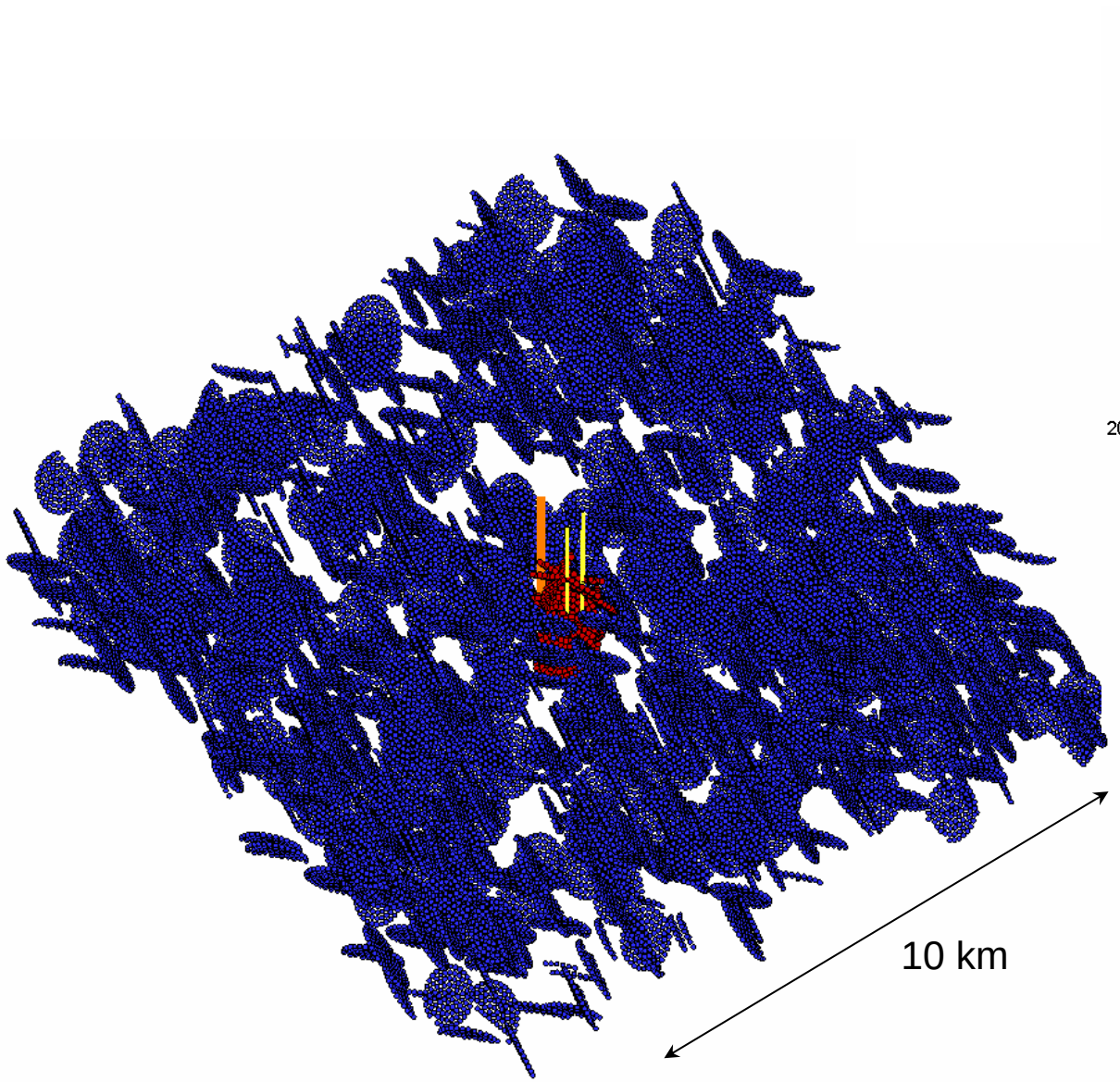
34-9RD2

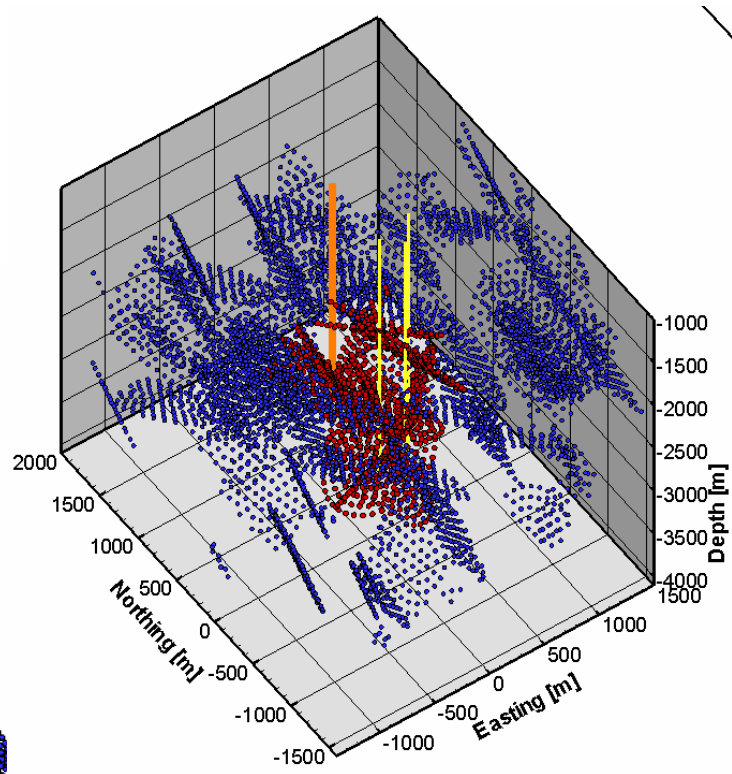


Coso Model:
Deterministic FZ in HEX-S model



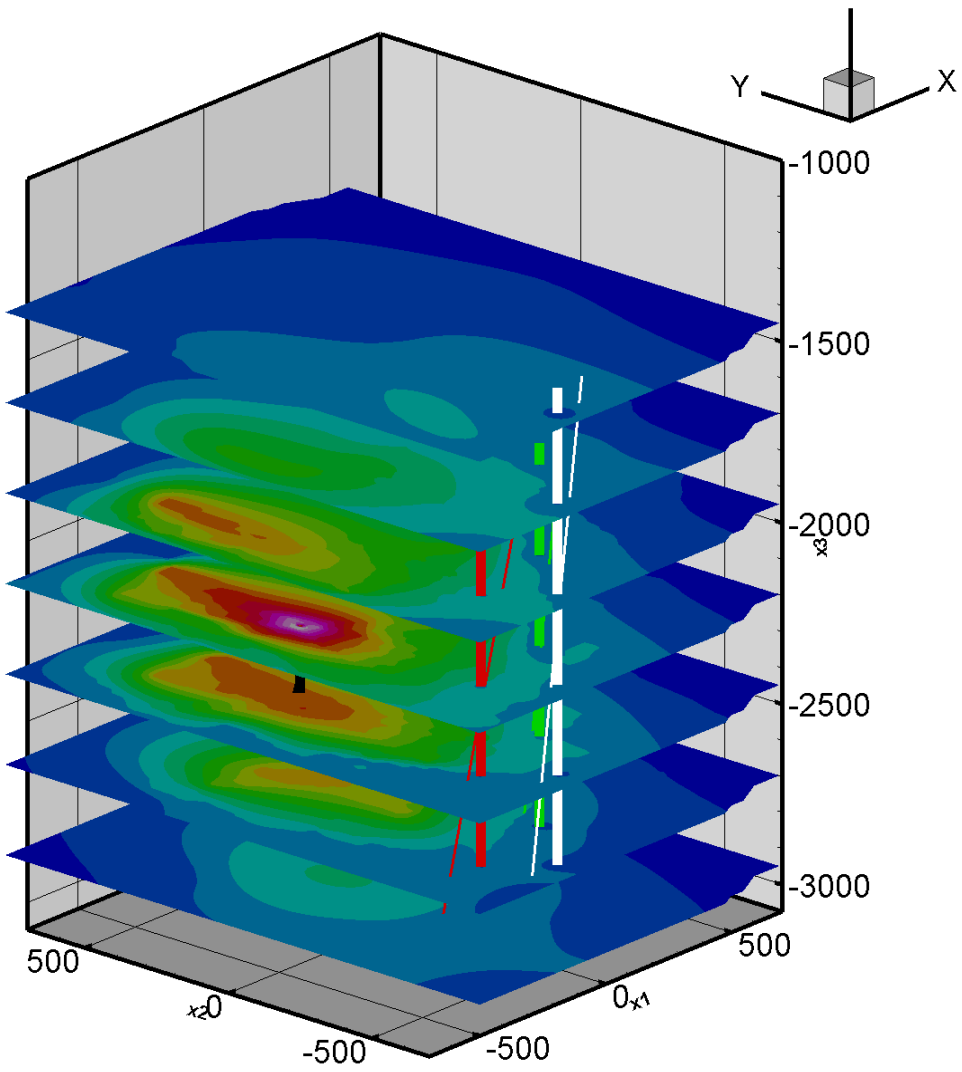
Coso Model:
Stochastic & Deterministic FZ





Coso:
3D Hydraulic Model

Pressure distribution around 34-9 RD2



- Strongly anisotropic pressure distribution
- Radial field only around injection point
- Pressure envelope oriented along fracture orientation
- Pressure wave propagation in areas with highest degree of fracturation

Coso:
First model calculations

Possible development of microseismicity